Peatland Hydrological Dynamics in Northern Minnesota

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Dedication

This thesis is dedicated to Scudder House and friends, as well as NRAGS. Thanks for keeping me balanced, everyone.

Abstract

I investigated peatland water table elevation responses to large precipitation events and long precipitation-free periods for a fen, poor fen, and bog, and pore water chemistry trends in a fen boundary zone, in northern Minnesota. Water table change compared to both precipitation and dry periods was slower in the fen than the poor fen or bog, a response attributed to connections between the fen and the regional groundwater aquifer. Water table change compared to larger dry periods remained consistent over a 51-year period and among peatlands. Calcium-silicon ratios in fen pore water were collected along transects perpendicular to the fen boundary. Larger calcium-silicon ratios at edge of the fen were interpreted as originating from a regional aquifer source, with minimal influence from vegetative calcium uptake and upland subsurface runoff. The extent of the fen-upland boundary zone was demarcated where calcium-silicon ratios matched average fen and stream outlet calcium-silicon ratios.

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INTRODUCTION

Peatlands have been observed and studied at the Marcell Experimental Forest (MEF) in northern Minnesota for over 50 years, providing a prolific amount of knowledge on peatland soil, hydrology, and biogeochemistry. My thesis expanded on the extensive catalog of research from MEF in two ways. First, I examined peatland water table elevation responses to large precipitation events and extended dry periods, comparing responses among peatland types and across time. Second, I determined calcium-silicon ratios in peat pore water in the boundary zone of a fen to discern chemical trends where the fen and surrounding uplands make contact. My thesis utilized historical and recently collected data to gather new insights into peatland hydrological response characteristics and spatial changes in peatland pore water chemistry.

CHAPTER 1: Peatland Water Table Dynamics During Large-Magnitude Precipitation and Extended Dry Periods

Introduction

The presence of a peatland in a watershed influences the water budget, the degree of surface saturation, and streamflow patterns (Holden, 2005; Bay, 1968). Peatland water tables vary with inputs and outflows that include precipitation, evaporation, streamflow, and groundwater. The balance of these interacting water sources and sinks determines the hydrologic regime of a peatland, which has feedbacks on biological communities and ecosystem function (Bay, 1968; Gafni and Brooks, 1990). Therefore, a greater understanding of peatland hydrology may lead to improved management of water resources throughout the northern United States and Canada. Greater knowledge of peatland hydrology is also needed in the context of greater growing season length, more days per year with high temperatures (Sebestyen et al., 2011), resulting in greater capacity for evapotranspiration (ET) (Boelter and Verry, 1977) in northern Minnesota. I present research in this chapter that increases knowledge of how precipitation influences peatland water tables over decades and in different peatland types.

There are generally two types of peatlands considered: bogs and fens (Figure 1). Bogs are disconnected from groundwater inputs and precipitation is the primary source of water during most of the year. Fens, in contrast, are connected to a large-scale regional aquifer or to localized aquifers that have developed because of regional topography (Boelter and Verry, 1977; Hogan et al., 2000; Reeve et al., 2001). Therefore, precipitation is less likely to affect water table elevation in fens because of large, consistent inflow from groundwater while bogs are more influenced by precipitation regimes. Groundwater flow through fens moves laterally and then upward to the surface at areas of high hydraulic conductivity and has a higher pH (Sander, 1976). An additional classification of peatland is the poor fen, which are disconnected from local groundwater like bogs, but have pH levels closer to that of a fen. Poor fens may have nutrient inputs from the surrounding uplands that result in higher pH and nutrient conditions richer than in other bogs.

Vegetation, which is a control on peatland ET, also varies among peatland types. In northern Minnesota, bog vegetation cover is commonly dominated by *Sphagnum* moss and black spruce *(Picea mariana).* Fen vegetation may also be dominated by *Sphagnum* species but generally has a much more diverse herbaceous, shrub and tree community than bogs. The varied vegetation in fens is due to the higher pH and nutrient peat pore water from groundwater (Boelter and Verry, 1977). ET is expected to have less influence on water table fluctuations in fens than bogs due to the hydrological connection to the surrounding groundwater aquifer, and precipitation inputs often balancing ET losses (Bidwell et al., 1970).

It is important that precipitation-water table dynamics are quantified to determine the influence of the regional groundwater and changes in ET on water table elevation on a precipitation event-based time scale. Studies of precipitation effects on water table elevation changes in wetlands over short periods of time are relatively numerous (e.g. Gerla, 1992; Bridgham and Richardson, 1993; Gilvear et al., 1993; Amon et al., 2002). Gerla (1992), for example, examined the relationship between water table and independent precipitation events in an intermittent wetland, focusing on how the mechanisms of vadose air pressure and capillary fringe can also lead to quick water table increases. Bridgham and Richardson (1993) and Amon et al. (2002) studied seasonal peatland water table changes, but did not examine the effect of large precipitation events on water table and did not quantify the relationship of dry periods and water table change. Bridgham and Richardson (1993) indicated that water table decreased generally for peatlands through the later summer and early autumn and increased in the winter and spring but Amon et al. (2002) confirmed that fens – even with season changes – have water table elevations relatively close to the peat surface. Gilvear et al. (1993) examined the overall water budget for fens to evaluate the concurrent influence of groundwater inputs and precipitation on shifting fen water table, but did not discuss intense rain or dry periods.

The need remains to quantify the relationship between individual event precipitation amounts or dry periods and water table elevations over the course of decades. My study quantified the precipitation/dry period-water table relationship for multiple peatland types (fen, poor fen, and bog) and over a multi-decadal time period. Multi-decadal analysis provided insight into overall hydrologic patterns as opposed to variability in year-to-year precipitation and allowed for the examination of change in precipitation/dry period-water table relationship compared to several decades of climate trends.

I hypothesized that large-scale precipitation events (both high rainfall events and extended dry periods) would result in larger changes in water table elevation responses for bogs and poor fens than fens due to the consistent and larger influxes of groundwater into fens compared to bogs. Furthermore, changes in climate, reflected by increasing temperatures, may increase the rate of water table decrease through evapotranspirative-drawdown during dry periods (Boelter and Verry, 1977) thus resulting in greater water table change in bogs, which are more influenced by precipitation and ET.

Methodology

The relationship between two types of events, large-scale precipitation events and extensive periods without rain (dry days), and their respective changes in peatland water table elevations were analyzed over 11 years among three peatland types, bog, fen, and poor fen, (henceforth known as the '11-year analyses'). The eleven year period was chosen as it was not so long as to encapsulate any potential long-term climatic changes that could have a confounding effect on precipitation-water table interactions so the different characteristics of the peatland types could be analyzed independently. I also examined the relationship of the duration of dry period to change in water table elevation over 51 years (henceforth known as the '51-year analysis') in the bog and fen.

Site Descriptions

I analyzed data collected in peatland watersheds within the Marcell Experimental Forest (MEF), a part of the USDA Forest Service Northern Research Station in northern Minnesota, USA (Figure 2). Sandy glacial outwash constituting an unconfined aquifer underlies the peatlands in this study (Sander 1976). MEF has a continental climate with dry, cold winters and humid summers with more precipitation than in winter. Average annual temperatures have increased by approximately 2 °C between 1961 and 2011 at the MEF (Sebestyen et al., 2011). When divided by season, mean air temperature has significant increases only between January and March and between June and August. Data from three research watersheds at the MEF were analyzed: S2 (containing a bog), S3 (containing a fen), and S6 (containing poor fen) (Figure 2). Data from the S2 and S3 watersheds were used for a 51-year analysis of dry day events as well as the 11-year analysis. S6 data, however, was only used for the 11-year study because data for this peatland were not available over the 51 year period.

The S2 watershed is 9.7 ha, of which 3.2 ha is covered by the S2 bog. The maximum elevation is 430 m above mean sea level and the minimum is 420 m at the outlet. Black spruce is the main forest cover species in the bog. The S3 watershed is 72 ha of which 18.6-ha is fen. The watershed ranges from 412 m elevation at the outlet to 429 m in the upland. The dominant species in the fen are black spruce, alder (*Alnus viridis crispa*), and willow (*Salix nigra*) (Kolka et al., 2011). S6 is an 8.9 ha watershed with a 2.0-ha poor fen. The highest elevation of the watershed is 435 m, with the peatland outlet at 423 m. Black spruce and eastern larch *(Larix laricina)* are the dominant tree species in the peatland (Kolka et al., 2011).

Streamflow from the S3 fen is perennial. Previous modeling indicated the S3 fen discharged more water to the surrounding groundwater aquifer during wet periods than dry periods and released more water through ET during dry periods than wet periods (Sander, 1976), though both ET and discharge to the aquifer can occur during wet and dry periods. Streamflow from the S2 and S6 watersheds is intermittent as a result of the perched water table and flows mainly in the spring and early summer, during large summer events, and in the autumn when transpiration losses decrease.

Hydrological Data

Daily precipitation data at the S2 watershed have been collected since 1961 using recording gages (Sebestyen et al., 2011). S2 precipitation data were used for all three peatland systems because it is the longest running record and within three kilometers of all the watersheds. Daily water table elevation data were available from peatland wells since 1961 for S2, since 1962 for S3, and since 1964 for S6 (Figure 2).

The analysis was limited to summer months, during active transpiration and after snow melt is no longer an influence on hydrology. During this period from June through September in which temperatures exceeded 0 °C, precipitation always occurred as rainfall, and not as snow that may have accumulated in a snowpack. The influence of snowmelt on water table elevation generally ceases by the beginning of June (Kolka et al., 2011). Summer conditions typically continue through September until the first period of five straight days of daily low temperatures at or below 0 °C. A five-day period of lows at or below freezing temperature in the autumn of a continental climate was considered as the end of warm, summer conditions and signaled the period when intermittent freezing influenced water table-precipitation relationships.

To determine changes in the water table elevation-precipitation relationships over time, the 51-year records were divided into four distinct semi-decadal hydrological time periods for comparison, using a methodology similar to Watras et al. (2014). Average daily precipitation was calculated by taking total annual precipitation amount and dividing by days in the given year. A change in average daily precipitation between years was used as a basis for semi-decadal hydrological time periods when compared with the average daily precipitation over 51 years. In particular, I identified periods in which annual daily average precipitation was above, at, or below the 51-year daily average. These periods would serve as examples of relatively wet or relatively dry periods. A 1961 to 1975 hydrological period was characterized by oscillation around the 51-year daily mean precipitation (0.21 cm). The 1976 to 1991 period began with a very low precipitation year, followed by oscillation around the 51-year mean. Annual average daily precipitation for the 1992 to 1999 period was consistently greater than the 51-year annual average daily precipitation. Finally, the 2000 to 2011 period was characterized by annual average precipitation below the 51-year average (0.21 cm) (Figure 3).

Hydrological Analysis

Dry Day Analysis (for 11- and 51-year analyses)

I examined the relationship between continuous days without rain (duration of dry days) and change in base water table elevation during the cumulative dry periods. Base water table elevation is the portion of the water table elevation that is not attributed to precipitation or shallow subsurface upland inputs from a recent event (Figure 4). Shallow subsurface flow would move across the surface of the uplands then infiltrate into peat. Therefore, total water table elevation would equal base water table elevation with additions of precipitation and/or surface recharge (Figure 4). A dry day was any day in which rainfall was recorded as < 0.3 cm. Based on inspection of the MEF precipitation record, rainfall events < 0.3 cm had negligible effects upon the water table elevation. Dry days periods of 10 or more sequential days with rainfall events < 0.3 cm were compared to the change in water table elevation. Dry day durations of nine days or less were very common in the precipitation record and were not used for analysis of low-frequency and high water-table influence events. The start and end of events were determined from water table recession analysis. I subtracted the base water table elevation at the start of the event from the elevation at the end of the dry-day event to calculate the change in water table during dry periods.

A recession filter separated changes in water tables due to precipitation events from base water table elevation. Changes in base water table elevation were then reflective of drying between precipitation events. A recursive filter equation for recession analysis from Nathan and McMahon (1990) was used:

$$q_k = \alpha * q_{k-1} + \left(\frac{1+\alpha}{2}\right) * (y_k - y_{k-1}) \qquad (Eq.1)$$

where q_k was the quickflow on day k and y is the water table elevation. The filter parameter (α) was set equal to 0.94 and was calibrated for hydrologic environments with long recession periods similar to peatland water tables (Eckhardt, 2008; Nathan and McMahon, 1990). Quickflow was defined as the portion of the water table elevation that is attributed to surface runoff, infiltration, and vadose zone subsurface flow entering the peatland.

For the 11-year analysis, correlation of dry period duration with change in base water table elevation was tested for data between 2001 and 2011 for S2, S3, and S6 peatlands using this generalized linear model:

$$y = m * [x] + C \qquad (Eq. 2)$$

where *y* is the change in base water table elevation (m), *x* is the dry period duration (days), *m* is the slope of the linear relationship between *y* and *x*, and *C* is a constant intercept value determined by the equation. The statistical significance level was set at $\alpha = 0.05$, and outliers were identified with a Bonferroni outlier test (Weisberg, 2005). A Tukey range test (with the hypothesis rejection significance level at $p > 0.05$) was also used to determine if the relationship between dry day period duration and change in base water table elevation differed significantly between watershed types (Weisberg, 2005). The same procedure was used for the 51-year analysis of dry days for S2 and S3, except the Tukey test was utilized to determine if the dry day – base water table relationship changed between the semi-decadal hydrological periods for each peatland type instead of between different peatland types.

Large-Magnitude Rainfall Analysis (for 11-year analysis)

The 11-year analysis was an examination of the relationship between large-magnitude rainfall (depth of precipitation) and event duration (in days) as defined in Equation 1. A bog, fen, and poor fen were subjected to this analysis to determine the effects of precipitation on water table elevation of different peatland types. Event duration was the accumulated consecutive days during which $q_k > 0$ (Equation 1). Large-magnitude rainfall events between 2001 and 2011 were defined as the largest 30 to 45 events, depending on the watershed. With lower magnitude events, there was a threshold (2 cm or recurrence interval of 0.12 years) at which events of the same magnitude became increasingly common in the historical record and thus were not included in the analysis. Because water table elevations may have peaked once after multiple closely-spaced rainfall events, rainfall the day before and after the event was added to account for any rainfall that crossed multiple days. The second day before the large-magnitude rainfall was also added to the total precipitation value if precipitation exceeded 0.5 cm or if the cumulative precipitation of the two previous days was greater than 0.5 cm. A rainfall event of this magnitude could be reflected in the same event peak in the water table record and was grouped in the same event. Rainfall that occurred more than one day after an event was not included in total rainfall calculation as this new rainfall event would result in a distinct rise in the water table elevation record and would thus have an independent effect on water table elevation. This independent and distinct water table increase was easily distinguishable in the hydrograph.

Determining the statistical influence of a rainfall event on the linear model required the use of DFFITS (degree to which a given data point alters the fitted value from the generalized linear model), covariance ratios, and Cook's distances values (Weisberg, 2005). Influential data points may require special examination when discussing overall trends in rainfall event/water table elevation relationships. I utilized a generalized linear model to determine the relationship between quickflow event duration (in days) and the amount of the large-magnitude rainfall event. The model took the form:

$$q = m * [x] + C \qquad (Eq.3)$$

where q is the number of quick flow event days, x is the depth of precipitation (cm) corresponding to q, m is the slope of the linear relationship between q and x, and C is a constant intercept value determined by the equation. A Tukey range test (with the hypothesis rejection significance level at $p > 0.05$) was used to determine if the relationship between q and x significantly differed between bog, fen, and poor fen watersheds (Weisberg, 2005).

Results

Dry Day, 11-year analysis

Between 2001 and 2011, dry day analysis was performed at the S2 bog, S6 poor fen, and the S3 fen with the longest dry day period between these dates occurring in 2007 and lasting 28 days. The 28 day dry period resulted in a 0.19 m decrease in base water table elevation for the poor fen, a 0.09 m decrease for the fen, and a 0.30 m decrease for the bog. Independently, each watershed demonstrated a statistically significant relationship between dry period duration and the change in base water table elevation, showing that longer dry day periods resulted in greater decreases of base water table elevation (Table 1, Equation 2). The slope (coefficient) of dry day period of watershed S3 was different from both watersheds S2 and S6, which were not statistically different from each other (Table 2, Figure 5). While S2 and S6 were statistically similar, with Tukey p-value of 0.070, this similarity was just outside of the set significance level ($p = 0.05$) that would constitute a statistical difference.

Dry Day, 51-year analysis

Between 1961 and 2011 at the S2 bog, the generalized linear model (Eq. 3) yielded a statistically significant relationship (dry day coefficient = -0.0065; p = 3.18 * 10^{-6}) between water table elevation and dry period duration, with larger decreases in water table base elevation occurring as dry period durations increased. All semi-decadal hydrological periods show significant trends when analyzed independently (Table 3, Figure 6), with the base water table decreasing significantly as the dry period duration increased. A Tukey test indicated there was no significant change in the relationship between the dry day duration and water table elevation across the semi-decadal hydrological time periods (Figure 3). Tukey testing between each hydrological period was: between 1961-'75 and 1976-'91: p = 0.76; 1976-'91 and 1992-'99: p = 0.78; 1992-'99 and 2000-'11: p = 0.16). The longest dry day period observed was 38 days (resulting in a base water table decrease of 0.21 m) and occurred in 1976.

Between 1962 and 2011 at the S3 fen, the generalized linear model (Eq. 3) yielded a statistically significant relationship (dry day coefficient = -0.0017; p = 3.21 * 10^{-6}) between water table elevation and dry period duration. As in the S2 bog, the S3 fen shows a significant linear correlation for each hydrological time period (Table 4, Figure 7). One 10-day dry period from the 1976-1991 hydrological period was found to be an outlier with the Bonferonni method and was removed as the hydrologic period did not gain significance with the inclusion of the data point. The Tukey test for slope coefficient showed that the slope does not change between hydrological time periods at S3. (1961-'75 and 1976-'91: p = 0.44; 1976-'91 and 1992-'99: p = 0.49; 1992-'99 and 2000-'11: p

= 0.85). The same 38 day dry period that resulted in base water table decrease of 0.21 m in the S2 bog caused only a 0.07 m base water table decrease in S3.

Large-Magnitude Rainfall, 11-year analysis

Large-magnitude rainfall events between 2001 and 2011 in the S2 bog, S3 fen, and S6 poor fen watersheds ranged from 7.69 cm to 19.20 cm. The 19.20 cm rainfall event (a 51-year storm on June 22, 2002) was removed from the record for analysis. The rainfall event was removed not as a statistical outlier but because of its much higher magnitude compared to all other rainfall events. Furthermore, because no other events were near the same magnitude (the next largest storm was approximately 9 cm or an 11-year storm), the 19 cm rainfall could have triggered additional hydrologic pathways that affected water tables beyond those in more frequent events. Bay (1969) indicated that bogs with high water tables that then experience intense rainfall have resulting large peak stream flows (relative to lower water tables). Increased streamflow may have occurred after this 19 cm event. Precipitation events from 2001 to 2011 ranged in magnitude from approximately 2 cm to 9 cm. Each watershed independently demonstrated a significant positive relationship between magnitude of precipitation event and duration of quickflow (Table 5). As with dry day analysis, the Tukey test between watersheds is further evidence that the S3 fen had a different hydrologic response from the S2 bog and the S6 poor fen, which exhibited similar responses (Table 6, Figure 8).

Large-Magnitude Rainfall, 51-year analysis

Large-magnitude 51-year rainfall event analysis was also attempted at the S2 bog. However, the expected linear relationship between precipitation and quickflow days (investigated with the same methodology for precipitation-quickflow relationship in the 11-year analysis) did not remain statistically significant. At approximately 11.5 cm rainfall events, the linear relationship was no longer present, and increasing precipitation did not result in longer quickflow periods. Many factors could have contributed to the lack of significant correlation for the rainfall 51-year analysis. Perhaps precipitation remains on the surface of peat soils as pores becomes saturated and can no longer hold large-magnitude rainfall levels. Or streamflow decreases existed at the outlet of the S2 bog during large-magnitude rainfall events that would cause a change in the relationship between rainfall depth and water table elevation. As a linear relationship proved inappropriate, I decided that the large-magnitude rainfall-quickflow relationship was more complex than the 11-year rainfall analysis in this chapter. Since describing the large-magnitude rainfall-water table relationship would therefore require analysis of other hydrologic relationships beyond water table elevation-precipitation interaction, such an undertaking would fall outside the goals of my thesis. I therefore concluded that 51-year rainfall analysis should not be included in this chapter.

Discussion

Dry Day, 11-year analysis

The results indicated the fen had different water table elevation responses to dry day period duration than the poor fen and bog. The smaller dry day slope coefficient of the S3 fen (-0.0032) compared to -0.0109 and -0.0073 for the S2 bog and the S6 poor fen slopes, respectively, indicated that the water table elevation in the S3 fen decreased less with increasing dry period duration (Figure 5). I attribute the significant difference between the S3 fen and other peatlands to the input of regional groundwater to the peatland throughout the dry day periods. The prominence of groundwater influence has been observed in fens in multiple locations across the United States (Amon et al., 2002; Bedford and Godwin, 2003). Groundwater sustained the S3 water table elevation even with decreased precipitation. As demonstrated in fens located in England, however, extended periods of drought that reduce surrounding aquifer water discharge can reduce inflow to the fen (Large et al., 2007). It is therefore possible that prolonged rainless periods (those longer than the 28 days maximum observed in the 11-year period), when groundwater input would continue to decrease, base water table elevation loss rates could decrease beyond that observed in your 11-year analysis.

Despite being semantically classified as a poor fen, the S6 peatland behaved hydrologically similarly to the S2 bog because of local topography. The geometry of the S6 watershed has a higher upland area:peatland area ratio than the S2 bog (Figure 2), which I hypothesize leads to higher upland runoff contributions. Upland runoff tends to have a higher pH than precipitation and that could lead to higher pH at the S6 watershed outlet when compared to the S2 bog. Hence, the definition of S6 as a 'poor fen' reflects its chemistry and nutrient condition rather than it hydrological connection to a regional groundwater aquifer.

Daily rates of base water table elevation at the MEF peatlands ranged from -0.0004 cm/day to -0.90 cm/day for S2; -0.003 cm/day to -0.44 cm/day for S3; and -0.06 cm/day to -0.70 cm/day for S6. The extremely low end of the S2 range occurred during a 10 day dry period which began after extremely wet conditions which would result in increased water table levels. Water tables in blanket peatlands in northern England decreased 0.55 cm/day in May 1996 and 2.26 cm/day in June 1996 because of ET (Evans et al., 1999). Vegetation at these English fens included *Sphagnum, Eriophorum,* and *Calluna* and almost no tree species. Note however, that Evans et al. (1999) examined the water table hydrograph and not exclusively base water table change. The rates determined in Evans et al. (1999) were therefore inherently different to those seen in my research at MEF and it was unclear how much water table elevation decrease in the blanket peatland of northern England occurred in the baseflow component of the water table hydrograph. This reiterates the importance of this thesis in examining the effect of precipitation on base water table elevation. Differences in ET between MEF and English peatland would also result in different water table decrease rates. MEF average annual ET is 65%-66% of annual precipitation (Kolka et al., 2011) and average annual potential ET in English fens is 24%-34% (Evans et al., 1999). ET was a significant source of water balance loss for peatlands, which can correspond with a water table decrease provided water tables were near the surface (Kolka et al., 2011).

<u>Dry Day, 51-year analysis</u>

Despite an increase in annual average daily temperature of 2 °C over 51 years (Sebestyen et al., 2011) and the potential for increased ET (Boelter and Verry, 1977), the interactions between water table change and duration of dry periods in the S2 bog and S3 fen have not changed significantly in the five-decade long record. In the S3 fen, the older hydrological periods had a similar slope that was distinct from the newer hydrological periods with their own similar slope (Table 4, Figure 7), but these differences were not found to be significant. Just as in the 11-year analysis, I found that the fen water table recedes over a narrower range of water table elevation values than elevations in the bog and poor fen (Table 3 and 4). Moreover, the increase in average daily temperature has not corresponded with an increase in the frequency of long dry day periods (Figure 9). The data show that event-scale changes in the rates of decline in water table responses to dry day durations did not change over the 51-year record.

Vertical hydraulic conductivity has been shown to vary with depth in peats (Fraser et al., 2001; Verry et al., 2011). Previous research has shown that the rate of water table decrease in northern peatlands (like those at MEF) slowed with increasing duration of rain-free periods (Waddington et al., 2014). In contrast, my analysis – over both 11 and 51 years – showed no decline in water table recession rate, instead demonstrating a linear relationship between water table elevation and duration of dry conditions (as base water table elevation consistently had a significant decreasing linear relationship). A linear relationship was logical if porosity and water holding capacity were assumed to be consistent at the depth interval where water table changes occur in MEF peatlands. The peatland studied by Waddington et al. (2014) had increasing pore volume but smaller diameter pores with increasing depth, which could result in changes in water holding capacity and therefore a slowing rate of decrease in water table decline.

Large-Magnitude Rainfall, 11-year analysis

As with the dry day analysis, I found fen water table elevation decreased at a slower rate than bogs in response to the duration of quickflow events after precipitation. In the S2 bog and the S6 poor fen, I observed larger quickflow event responses to large-magnitude precipitation occurrences, as demonstrated by longer event durations as rainfall amount increased. Event length slopes for S2 and S6 were 0.99 and 1.25 respectively, while the slope for S3 (0.52) was less than those of S2 and S6 for the same rainfall magnitudes (Table 5, Figure 8). The Tukey test confirmed a statistically significant difference in slopes between S6 and S3 ($p = 0.004$), but the difference between S2 and S3 was only marginally significant ($p = 0.07$). It is possible that these generalized linear models could be combined with exponential models linking near surface and subsurface stormflow from the upland to the peatlands and water table elevation, thus creating more complete descriptions of water table elevation dynamics (Verry et al., 1988). However my research only examined precipitation and water table relationships. While my research quantified the effect of certain precipitation events on water table elevation, it did not fully explain water table elevation changes.

In blanket peatlands of the United Kingdom, where precipitation and corresponding upland overland flow input into peatlands has been shown to be the primary driver of water table increases during summer months, water tables increased at an average rate of 5.3 cm/hour (Evans et al., 1999). However, in these UK peatlands water table increases last only “over a period that is comparable to the duration of the rainfall” (Evans et al., 1999) whereas in MEF peatlands the water table elevation response to precipitation can last for days after a precipitation event. Between bog and fen types in northern Minnesota, the data show that peatlands respond differently to rainfall events depending on hydrologic setting, with bogs responding with higher rates of water table changes during large-magnitude precipitation and dry day periods.

Conclusions

The relationship between base water table elevation and dry day period in fens and bogs remained consistent across the entire 51-year record. The S3 fen water table elevation decreased at a slower rate than the bog and poor fen during increasingly long dry day periods. This conclusion is also valid for large magnitude rainfall and dry day relationships in both the bogs and fens. Therefore, the connection of the fen to the regional aquifer resulted in more stable water table elevation base conditions than observed in bogs and the poor fen. My results emphasize the importance of the groundwater connection to fens to maintain water table elevation levels.

My research also indicated that the bog and poor fen were similar hydrologic systems and therefore the terminology “poor fen” is indicative not of hydrological connection to regional groundwater, but of pore water chemistry.

Furthermore, the statistical relationship between base water table elevation and dry day length that each hydrological semi-decadal period did not change over 51 years despite greater growing season length and higher summer temperatures (Sebestyen et al., 2011) (which results in greater capacity for ET and therefore potential for a lower water table (Boelter and Verry, 1977)). The consistent relationship between base water table elevation coupled with a lack of increased frequency of dry day events indicated that there has not been an observable effect of changing climate on water table elevation – high magnitude dry day length dynamics at MEF. The strong relationship between decreasing base water table elevation and dry day length in the S2 bog and S6 poor fen remains as an important observation of peatland characteristics, however.

ILLUSTRATIONS – Chapter 1

Table 1: Dry day slope coefficients for three peatlands between 2001 and 2011 (using the Eq. 2 model). Each demonstrates that as dry day duration increases, change in water table also increases. For all three peatlands there is a clear statistically negative significant relationship that highlights greater decreases in water table elevation when dry day period increases.

MEF Watershed	Dry day coefficient	Intercept (C)
S2	-0.0109 ($p = 0.0006$)	0.0772 ($p = 0.0732$)
S3	-0.0032 ($p = 0.0040$)	0.0201 ($p = 0.1945$)
S6	-0.0073 ($p < 0.0001$)	0.0454 ($p = 0.0269$)

Table 2: Test for significant differences in dry day slope coefficients between each watershed for 2001 through 2011 (using the model described in Eq. 2). The S3 fen is dissimilar compared to both the S2 bog and the S6 poor fen, which have similar slope coefficients. The different S3 dry day slope coefficient demonstrates that groundwater connection of the S3 fen resulting in less of a decrease in water table elevation during increasing dry day length is statistically significant when compared to the S2 bog and S6 poor fen

Watershed Relationship	p-value
S3-S2	< 0.001
S6-S2	0.070
S6-S3	0.006

Table 3: Coefficients for generalized linear model relating dry day period to change in water table with Eq. 2 for the S2 watershed. During all hydrological periods, there is a statistically significant relationship between increasing dry day length and greater decreases in water table elevation. Note: only 18 data points existed for the 1992-1999 hydrological period.

MEF Hydrological Period	Dry day coefficient	Intercept (C)
1961-1975	-0.0053 ($p < 0.0001$)	0.0277 ($p = 0.0185$)
1976-1991	-0.0062 ($p < 0.0001$)	0.0326 ($p = 0.0706$)
1992-1999	-0.0047 ($p =0.0035$)	0.0130 ($p = 0.5075$)
2000-2011	-0.0111 ($p = 0.0002$)	0.0828 ($p = 0.0380$)

Table 4: Coefficients for generalized linear model relating dry day length to change in water table with Eq. 2 for the S3 watershed. During all hydrological periods, there is a statistically significant relationship between increasing dry day length and greater decreases in water table elevation. Note: only 18 data points existed for the 1992-1999 hydrological period.

MEF Hydrological Period	Dry day coefficient	Intercept (C)
1961-1975	-0.0013 (p = 0.0172)	-0.0021 (p = 0.7934)
1976-1991	-0.0012 (p = 0.0401)	-0.0106 (p = 0.2212)
1992-1999	-0.0036 (p = 0.0026)	0.0283 (p = 0.0613)
2000-2011	-0.0033 (p = 0.0019)	0.0209 (p = 0.1396)

Table 5: Coefficients for the relationship between precipitation and water table increases for large rainfall events in a bog, poor fen and rich fen at the Marcell Experimental Forest (Eq. 3).

MEF Watershed	Precipitation coefficient	Intercept (C)
S2	0.989 ($p = 0.0015$)	4.621 ($p = 0.0020$)
S3	0.518 ($p = 0.0451$)	5.201 ($p = 0.0001$)
S6	1.253 ($p < 0.0001$)	4.257 ($p = 0.0023$)

Table 6: Differences in precipitation slope coefficients for three watersheds between 2001 and 2011 (using the Eq. 3 model). The slope coefficient for the S3 fen is statistically different than the slope coefficients for the S2 and S6 watersheds, which were not statistically different from each other.

Watershed-Relationship	p-value
S3-S2	0.0713
S6-S2	0.5337
S6-S3	0.0042

Figure 1: Diagram of fens and bogs (modified from Boelter and Verry, 1977). The lagg zone in a bog is the area where the peatland and upland make contact and there is high flow. Blue lines represent movement of water.

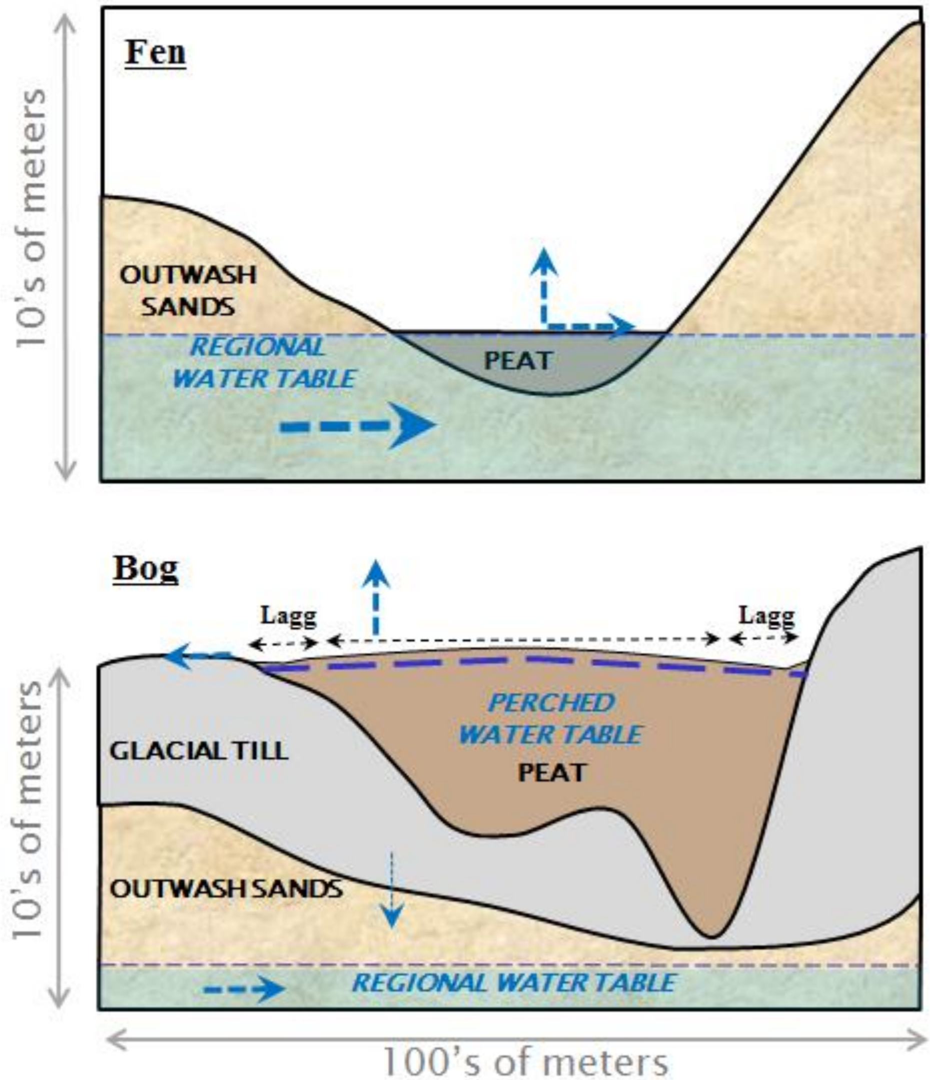


Figure 2: Site maps for the peatland watersheds utilized in this study and their location within the MEF and Minnesota. Peatland wells were used for measuring water table elevation (Study Site S2, 2007; Study Site S3, 2007; Study Site S6, 2007)

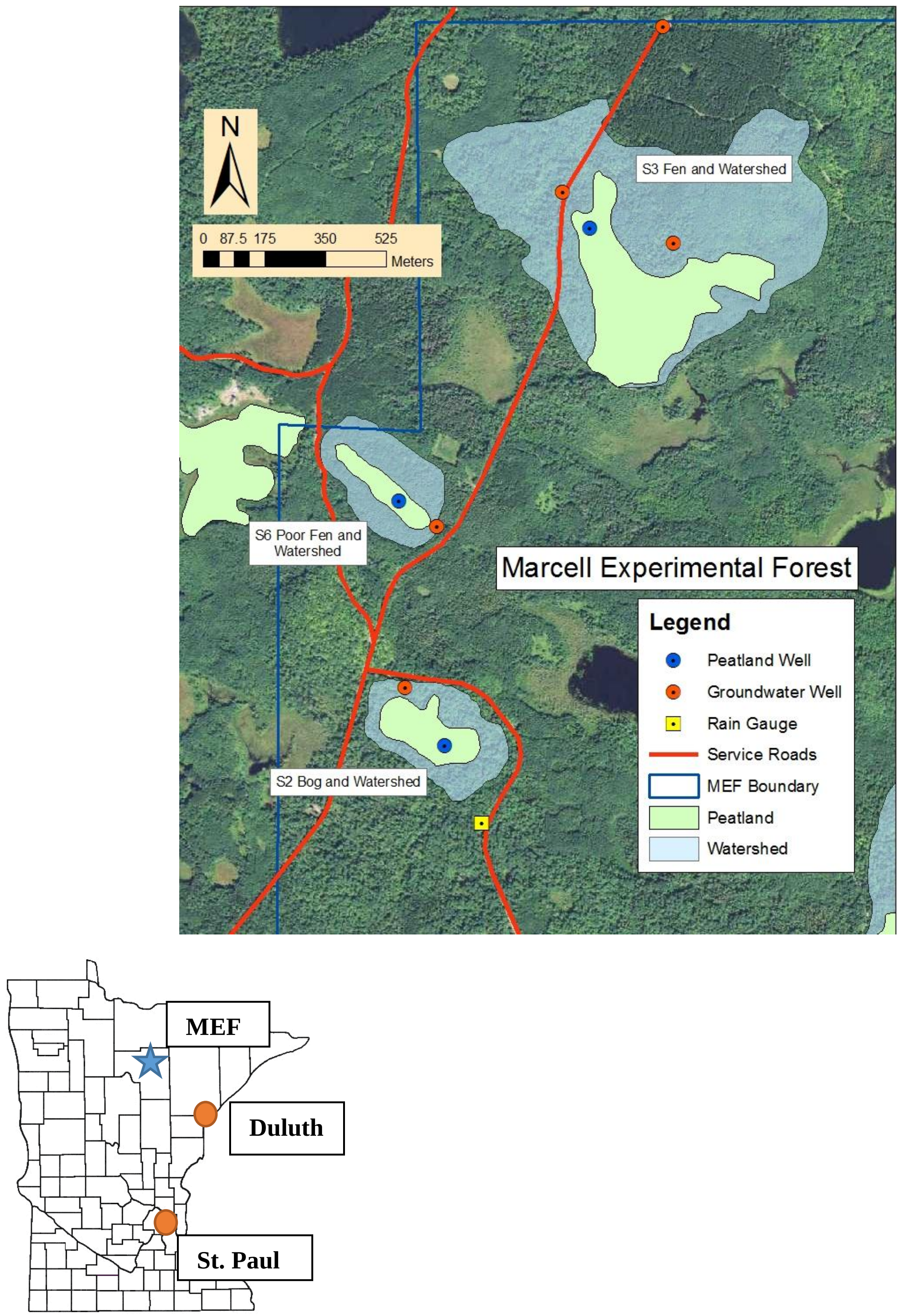


Figure 3: Division of the precipitation historical record based on changes and trends in annual daily average precipitation (y-axis). Black lines separate semi-decadal hydrological periods utilized for comparison over climatic trends.

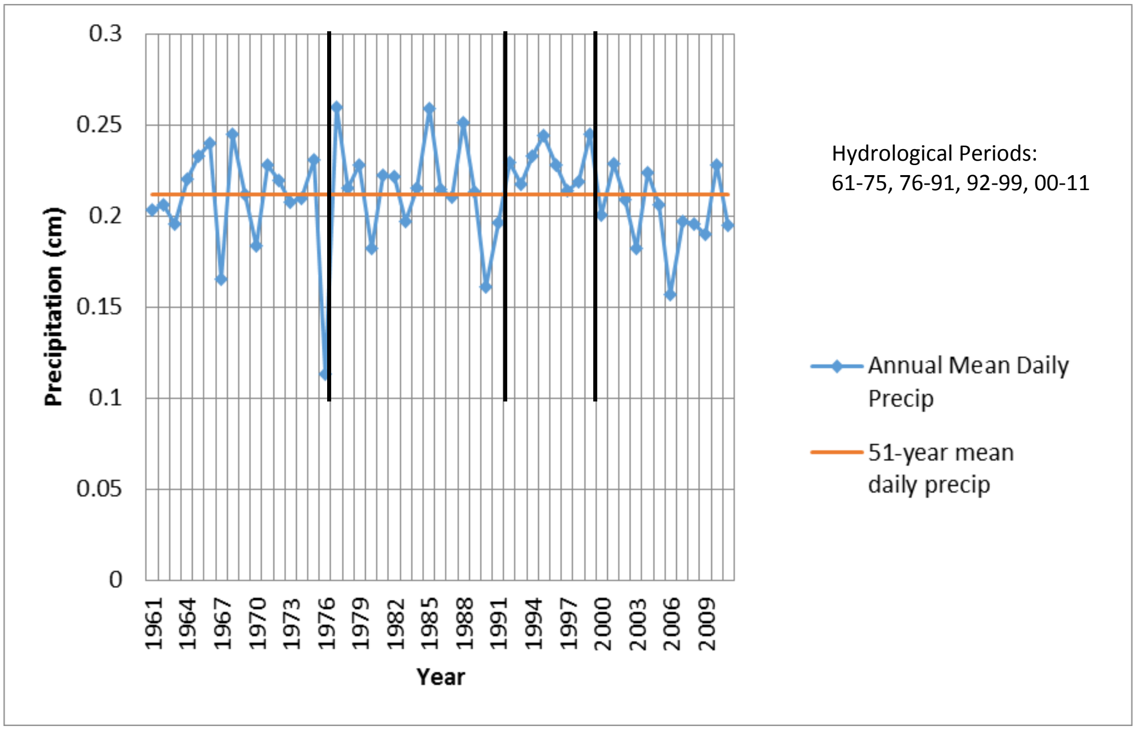


Figure 4: Example of base water table elevation and "quickflow" water table elevation from the S2 watershed. Water table elevation here is relative to a 421.32 m local minimum water table elevation

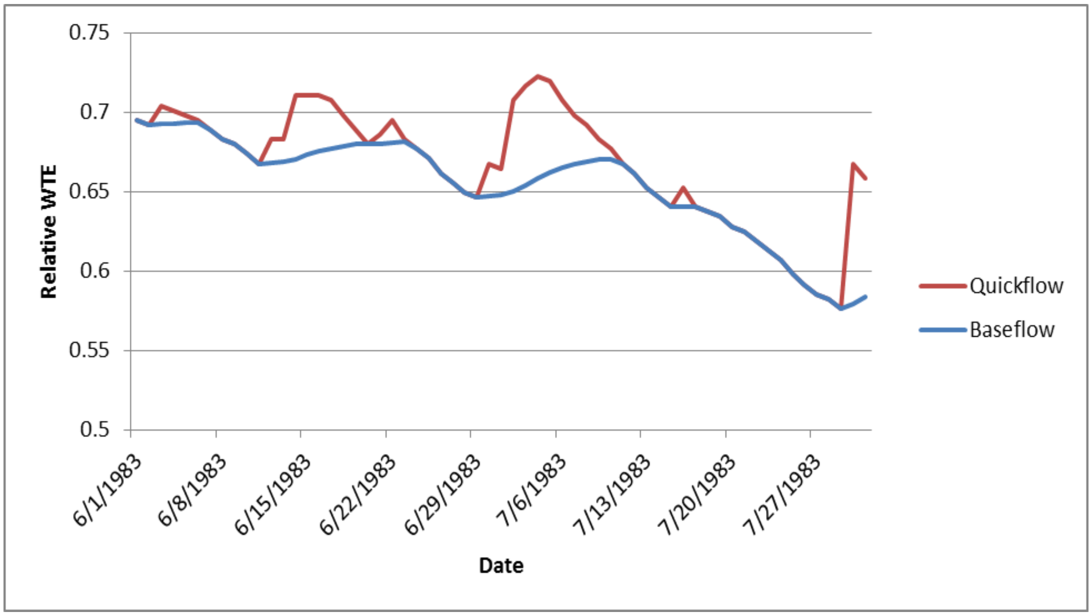


Figure 5: Dry day periods vs. change in base water table. The corresponding regression lines are in the same color as the data points. S3 fen is statistically different from S2 bog and S6 poor fen. The S2 bog and S6 poor fen have similar slopes. This figure demonstrates how the connection to groundwater present at the S3 fen results in a statistically different relationship between change in water table base conditions and dry day period compared to the S2 bog and S6 poor fen.

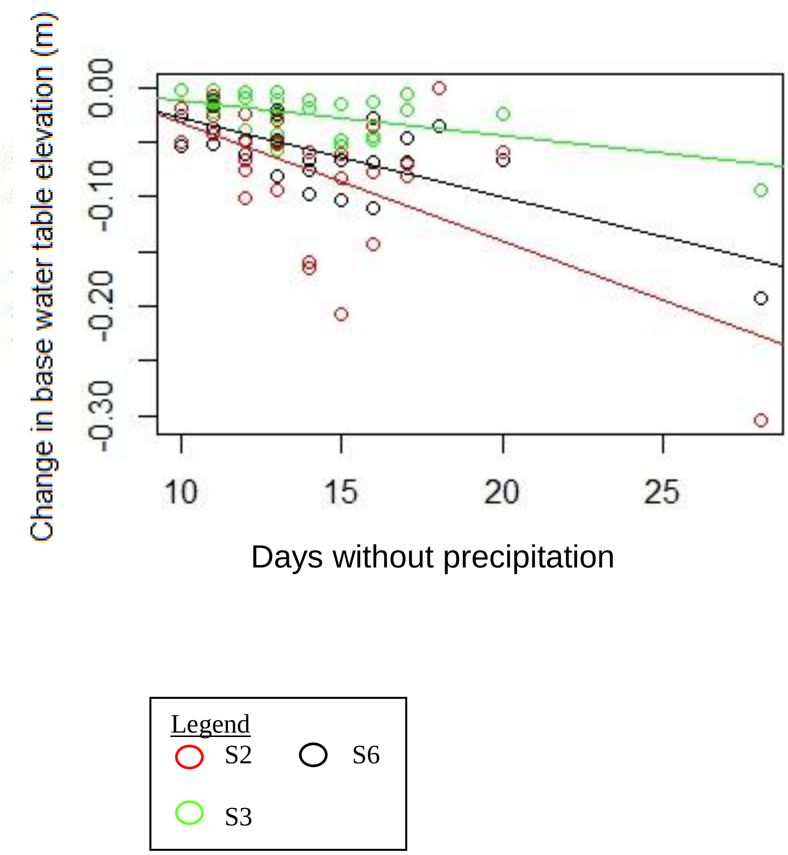


Figure 6: Dry day periods vs. change in base water table for each hydrological time period in the S2 watershed between 1961 and 2011. The corresponding regression lines are in the same color as the data points. Slopes were statistically similar.

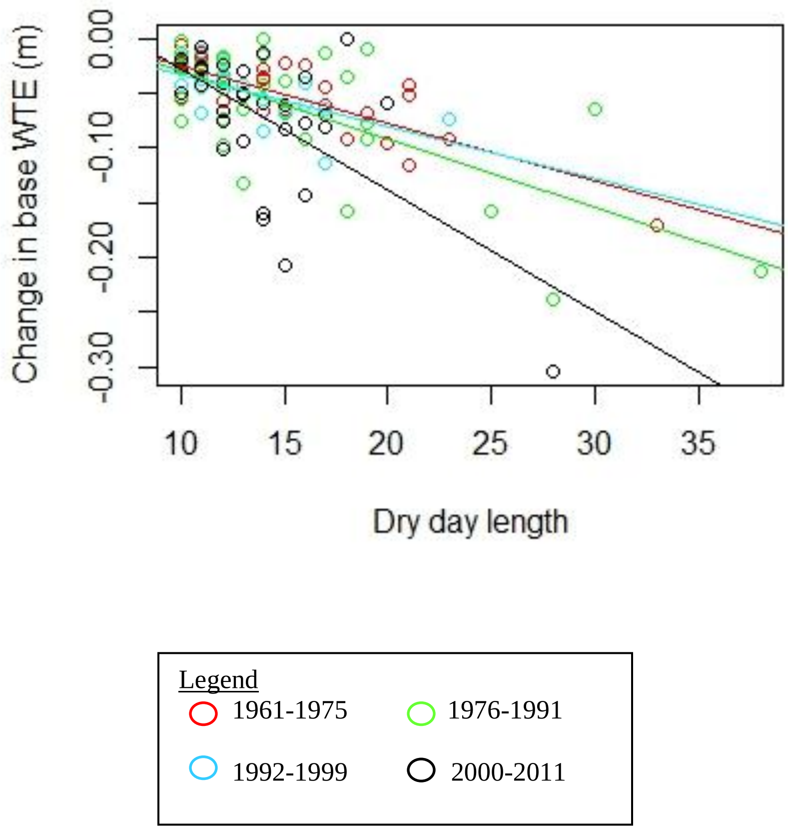


Figure 7: Dry day periods vs. change in base water table for each hydrological time period in the S3 watershed between 1966 and 2011. The corresponding regression lines are in the same color as the data points. Slopes were not statistically different.

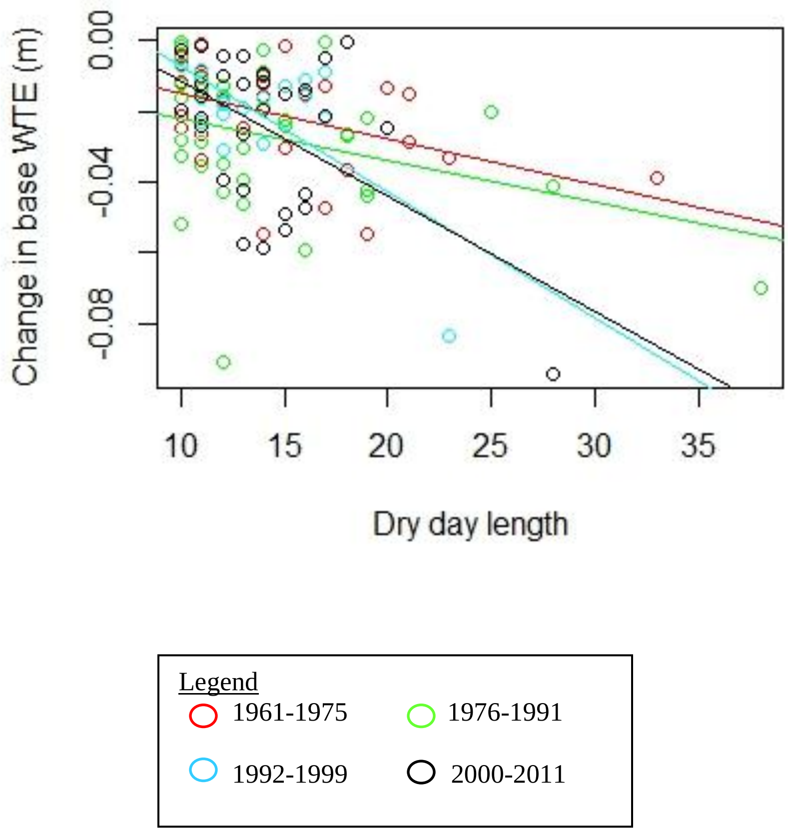


Figure 8: Relationship between event days of quickflow and rainfall measurements. Their corresponding regression lines are in the same color. The S3 fen is significantly different from the S2 bog and the S6 poor fen. The S2 bog and S6 poor fen have similar slopes. The similar S2 and S6 slopes demonstrated how the connection to groundwater present at the S3 fen results in a statistically different relationship between change in water table event days and precipitation event compared to the S2 bog and S6 poor fen; the number of rate of increase in event days is smaller for the S3 fen than for the S2 bog and S6 poor fen because influence from water table is a more powerful influence than precipitation inputs.

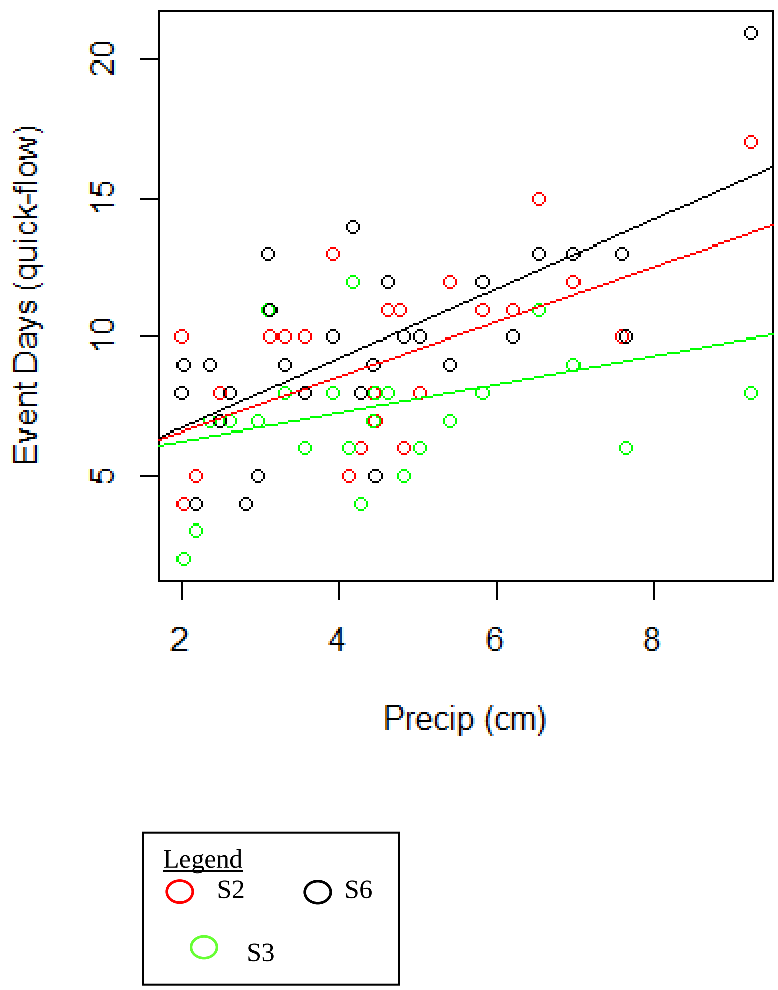
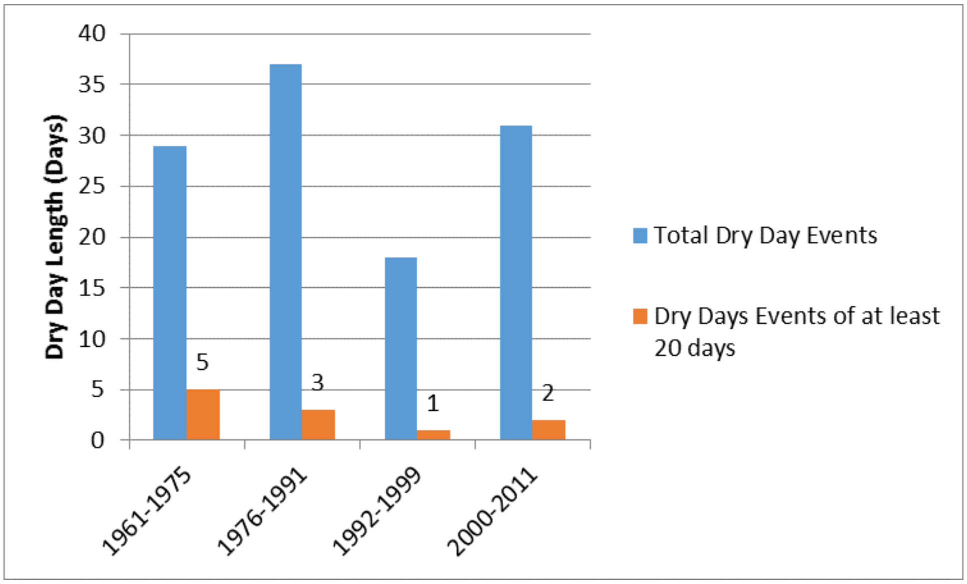


Figure 9: Frequency of dry day events in each hydrological period. Included is the number of dry day events that were at least 20 days long. There is no clear trend of increase or decrease of total dry day events over the 51 year record.



CHAPTER 2: Boundary Zone Fen Pore Water Chemistry

Introduction

The balance of precipitation, evapotranspiration, streamflow, and groundwater connectivity in a peatland determines its hydrologic regime, which has feedbacks on biological communities and ecosystem function, particularly plant species distribution (Bay, 1968; Gafni and Brooks, 1990; Koerselman, 1989). Fens are peatlands that receive most of their water from regional groundwater (Boelter and Verry, 1977; Hogan et al., 2000). Fens may be connected to a large-scale regional aquifer or to a localized aquifer depending upon regional topography and may be sources of recharge or discharge to surrounding water bodies during a given year but there may also be proximal influences from shallow subsurface flow from uplands within the watershed. Groundwater aquifers flow through glacial tills, which differ from shallow subsurface stormflow that moves through shallow soil layers and is derived from precipitation (Boelter and Verry, 1977). Little is known of upland subsurface influences on peat pore water and therefore this thesis will explore these areas (Koerselman, 1989; Reeve et al., 2001).

Connection to groundwater results in high cation concentrations from geological source weathering in fen pore water (Boelter and Verry, 1977). Boelter and Verry (1977) measured fen pore water calcium and silicon concentrations of 16.6 mg L^{-1} and 4.9 mg L^{-1}, respectively, in northern Minnesota. However, changes in pore water chemical concentration in the fen-upland boundary zone and the degree to which boundary zone peat pore water chemistry is influenced by infiltration, interflow, and subsurface stormflow from the surrounding upland are not well covered in existing literature (Amon et al., 2002; Bedford and Godwin, 2003; Boelter and Verry, 1977). In bogs – peatlands without groundwater inputs – the boundary zone (also known as a lagg zone) is a principal location of flow (Sander, 1976). Amon et al. (2002) have stated that the upland-fen point of contact is the only demonstrable boundary of a fen, but do not examine the chemistry or extent of that boundary. I investigated the characteristics of the fen boundary zone to compare and contrast the hydrology of bog boundary zones. Examination of pore water calcium and silicon could also demonstrate the physical extent of the boundary zone of the fen and the upland. I also investigated pore water calcium and silicon as tracers of sources of peat pore water and the interaction between fen vegetation and pore water chemistry. This chemical data exists in general for fens (Bedford and Godwin, 2003; Boelter and Verry, 1977), but is not focused on the boundary zone.

I hypothesized that calcium-silicon ratios within the fen boundary zone would remain similar to that of surrounding regional groundwater (with high calcium concentrations) because groundwater from the aquifer, with a consistent chemistry, should be the dominant source in peat pore samples (Boelter and Verry, 1977). Upland pore water would have lower calcium concentrations as well, with a rapid spatial transition of increasing calcium concentrations from the upland to the fen. The effects of this upland lateral flow on peat pore water chemistry will be assessed in this study.

Methodology

Site Description

I studied a fen in the S3 watershed at the Marcell Experimental Forest (MEF) in northern Minnesota, USA (Figure 10). The 72-hectare S3 watershed at the MEF contains an 18.6-ha fen and ranges in elevation from 429 m at its highest point to 412 m at the outlet (Figure 10). The watershed is underlain by sandy glacial outwash that serves as an unconfined aquifer (Sander, 1976). Regional groundwater, the primary water supply to the fen, generally flows from north to south (Boelter and Verry, 1977) with the depth to water often observed within 10 cm of the fen surface. Due to contact with the glacial outwash that forms the unconfined aquifer, regional groundwater tends to have higher concentrations of cations than precipitation (Boelter and Verry, 1977). Fen pore water pH is between 6 and 7.5. Groundwater flow through the S3 fen moves laterally and then upward to the surface at areas of high hydraulic conductivity. Shallow subsurface stormflow from the upland also enters the fen, but with small volume compared to groundwater movement through the fen (Sander, 1976).

Field-Experiment Design

Transect Organization

Nests with two depths of piezometers, made of 5.5 cm internal diameter PVC pipe, were used to collect water samples and measure water levels. The nested piezometers were organized into three transects parallel to the fen-upland gradient and perpendicular to the fen-upland boundary. Each transect consisted of six nested piezometers and extended from the aspen *(Populus grandidentata)* forest of the upland into the black spruce *(Picea mariana)* on the fen. Starting in the upland, the first two piezometer nests were placed directly in mineral soil (also known as piezometer nest U1), at 0.2-m and 0.5-m depths. A second piezometer nest (UF1, at 0.5 m and 0.7-m depths) was designed to sample from mineral soils under shallow peat layer (Figure 11). From these first two nests, waters from mineral soil were collected to compare with the peat pore water.

For the remaining peat piezometer nests, depths were 0.2 m and 0.5 m and placed in the hummock/hollow microtopography present in fens. The third nested piezometer position (UF2) was placed so the screened interval was at 0.5-m depth was at the mineral soil-peat boundary. The fourth (F1) and fifth (F2) nested piezometer positions only intersected peat (Figure 11), with F2 placed approximately where large fen tree species, such as black spruce and tamarack (*Larix laricina*) appeared (Figure 11 and 3). The F2 position was chosen to be representative of pore water cation concentrations in the presence of large peatland tree species. The last nested piezometer position (F3) was several meters into the fen from F2. The F3 location was entirely within and, presumably, hydrologically-influenced by the fen exclusively (Figure 11).

Transect Location and Vegetation

Transects were on the western edge of the fen and consisted of a northern, middle, and southern site (Figure 10). *Sphagnum* and some sedges were present at sites UF1 and UF2. Black spruce was present from F1 through the F3 (Figure 12a, 12b, 12c), with smaller black spruce around F1 than larger black spruce and tamarack beginning at F2. Aspen was the dominant species at the U1 site.

The northern transect was approximately 15 m long. The middle transect was 19 m long. At the middle transect, an alder zone grew near UF2, but approximately four meters away from the transect on either side. The middle transect essentially bisected a gap in the zone where alder was generally found in this part of the S3 fen, parallel the fen-upland boundary (Figure 12b). The south transect was 30 m long. Fewer black spruce were observed compared to the north and middle transects, and sedges were found from UF2 through F3. Alder was also found at sites UF2, F1, and F2 (Figure 12c). The south transect was the closest transect to the outlet of the fen at the southern end of the S3 watershed (Figure 10).

Data Collection and Analysis

Depths to water were measured and water samples were collected on 12 occasions from each piezometer approximately every week between mid-June and mid-September of 2013. I sampled piezometers after rainfall when possible to collect upland samples from the transiently saturated zone that may be representative of shallow subsurface flow from upland soils. On each collection day, I first measured depth to water with a sounding water depth sensor (Solinst Mini Water Level Meter, Model 102M or Waterra Water Level Sensor WS-2 Closed Reel) and piezometer height above peat surface to determine the hydraulic head. I subtracted piezometer height above the peat from depth-to-water measurements to calculate depth of water below the fen surface. These depths to water were then corrected to transect-specific datums determined using a laser level to calculate hydraulic heads along each transect. Transect data were matched to USFS and Minnesota Department of Natural Resources LiDAR digital elevation models (Lefsky, 2008; MNDNR and Woolpert, 2014). I calculated hydraulic gradients across and among transects.

Piezometers were purged to remove stagnant water. Samples were pumped into 250 mL polyethylene bottles and chilled immediately in the field before transportation to the USDA Forest Service Northern Research Station in Grand Rapids, MN for analysis. Samples were analyzed for calcium and silicon. Measurements of calcium and silicon were made with a Thermo Elemental Iris Intrepid ICP-OES according to EPA Standard Method 3120 (USEPA, 2010). Detection limits for both calcium and silicon were 0.05 ppm and sampling was checked by repeated-sampled analysis for every tenth sample. The concentration of several other solutes was also measured. These solutes and methodologies can be found in the Appendix. Calcium and silicon concentrations in precipitation from an event-only precipitation collector (approximately one mile from the S3 peatland) and the S3 stream outlet from 2008 to 2012, were used for comparison with peat pore water concentrations. Precipitation volume was measured with a standard gauge within the S3 watershed (Sebestyen et al., 2011). Precipitation and stream water quality data were provided by the USDA Forest Service Northern Research Station in Grand Rapids, MN and were measured for calcium and silicon using the same method as for peat pore water.

The large influence of groundwater in peat pore water is reflected in the high calcium concentrations. However, determining the influence of small changes in peat calcium concentrations was challenging. Using silicon – which had a consistent concentration among all piezometers - as the denominator term in calcium-silicon ratios meant that small variations in calcium could be interpreted as changes in chemical characteristics of the peat pore water. Silicon was therefore used as a reference cation against which changes in calcium concentrations could be determined, so calcium-silicon ratio was chosen as the metric to examine peat pore water change in the boundary zone. Both silicon and calcium are generally dissolved from geologic materials into groundwater, but silicon is generally found at lower concentrations than calcium (Groundwater, 1999; Groundwater Quality, 2003).

Examination of calcium and silicon simultaneously for different water sources that input to fen pore water can identify similarities in water chemistry and influences of water sources through end-member mixing analysis. Chemistry of hydrologic inputs to the fen can constrain chemistry within pore water. This form of end-member mixing provides insight into how fen pore water and upland water sources can fractionally contribute calcium and silicon to surface water leaving the S3 fen (Mulholland, 1993).

I used a pairwise t-test with the p-values adjusted with the Bonferroni method to determine the statistical differences between calcium-silicon ratios between piezometers along each transect (F-values with significant level significant at $p \leq 0.05$). To determine if the pore water chemistry was different among piezometer location between transects (e.g. the similarity between the 20-cm U1 at the north and middle transects), I used a repeated measures ANOVA test. The F-statistic of the repeated measures ANOVA has the form:

$$F = \frac{\frac{SS_A}{df_A}}{\frac{(SS_W - SS_A)}{(df_W - df_A)}} \quad (Eq. 4)$$

In Equation 4, SS_A and df_A are the sum of squares and the degrees of freedom for all calcium-silicon data points. SS_W and df_W is the sum of squares and degrees of freedom for each piezometer location grouped among piezometers (e.g. the 20 cm U1 piezometer for the north, middle, and south transects).

I tested for significant differences at each piezometer location by depth among transects (F-values were significant at $p \leq 0.05$). Any piezometer in which no water was present was excluded from statistical tests. With the repeated measures ANOVA, I determined when chemistry was different among transects. The test only indicated if at least one of the three transects was significantly different from another transect. A pairwise t-test (with Holm methodology applied to p-value analysis) was used to specifically determine if a transect was significantly different from another ($p \leq 0.05$) (Girden, 1992; King, 2014). The repeated measures ANOVA-pairwise t-test method was also used to determine significant differences between calcium-silicon concentrations at varying depths at a transect for each piezometer. A standard ANOVA test was also used to test differences between pore water calcium-silicon ratios at specific piezometer locations and at the outlet of the S3 fen and to test differences between two groups of piezometer locations (e.g. testing the difference between the northern UF1 and middle UF1 calcium-silicon concentrations).

Results and Discussion

Patterns among transects

Calcium concentrations in fen and upland pore water ranged from 7.72 mg L^{-1} to 68.61 mg L^{-1}, with a mean concentration of 26.38 mg L^{-1} (Table 7). Silicon concentrations ranged from 4.57 mg L^{-1} to 25.95 mg L^{-1}, with a mean concentration of 9.94 mg L^{-1} (Table 8). Calcium-silicon ratios ranged from 0.56 to 8.29 with a mean ratio of 2.84 across all transects (Table 9). Silicon concentrations were stable between UF2 and F3 (11.49 mg L^{-1} mean with a 1.87 mg L^{-1} standard deviation at the north transect, 9.87 mg L^{-1} mean with a 1.08 mg L^{-1} standard deviation at the middle transect, 8.39 mg L^{-1} mean and 1.67 mg L^{-1} standard deviation at the south transect). Calcium concentrations were less stable between UF2 and F3: 13.59 mg L^{-1} mean and 5.21 mg L^{-1} standard deviation at the north transect, 36.90 mg L^{-1} mean with a 10.07 mg L^{-1} standard deviation at the middle transect, and 21.53 mg L^{-1} mean with a 6.91 mg L^{-1} standard deviation at the south transect. There was a general decrease of calcium-silicon ratios between UF1 and F3 for each transect (with some exceptions, especially at the southern F1 50-cm piezometer) (Figure 13).

Hydraulic head (in meters above sea level) ranged from 412.08 m to 413.94 m among the three transects, with the highest hydraulic head observations at the north transect (between 413.40 m and 413.94 m) and the lowest at the south transect (between 412.08 m and 412.66 m, Table 10, Figure 14) indicating groundwater flow moving from north to south. The hydraulic gradient was generally small along each transect, typically varying approximately 10 cm between UF1 and F3 (Figure 14). Therefore, most water moved from north-to-south not along the transects. Nonetheless, the influx of another water source would mean variation in the local hydraulic gradient of each transect.

<u>Transect Comparisons</u>

Lateral water movement across transects (compared to fen gradient from north to south), indicated by similar hydraulic head measurements in the 20-cm, 50-cm, and 70-cm peat piezometers at each position along all transects (Figure 14), lends to the conclusion that an influx of a different water source was unlikely to be the cause for the variations in calcium-silicon ratios observed across the S3 fen. Fifty-centimeter depth calcium-silicon ratios at U1 were significantly different from those at UF1 for the north and middle transects (Table 11). Lower calcium-silicon ratios at the upland sites (U1) at each transect could have been influenced by precipitation and corresponding shallow subsurface stormflow through as much as 55 cm of mineral soil (Figure 15). Calcium uptake from upland trees may have also lowered calcium-silicon ratios (Likens, 2013; McGuire and Likens, 2011).

Calcium-silicon ratios at the north transect were generally lower (Ca:Si range from 0.56 to 2.60) than those at the middle or south transects (Ca:Si range between 2.07 and 7.96 and between 1.19 and 8.29, respectively) (Table 9). For all 12 data collection dates the repeated measures ANOVA test indicated that at least one transect was different than another for each piezometer's calcium-silicon ratio. For all 12 collection dates the north transect displayed statistically lower ratios at each piezometer compared to the corresponding piezometer in the middle and south transects (Table 12). The middle transect and southern transect were also consistently significantly different from each other (Table 12).

The lower calcium concentration and calcium-silicon ratios at the north transect when compared to middle and south transects could have been due to multiple factors. First, composition of upland soil and parent material and resulting weathering products may vary among transects. Effects of vegetation uptake and cycling on calcium-silicon ratio may also vary among transects (Glaser, 1990; Likens, 2013). However, vegetation differences are unlikely to account for the entirety of the difference between the north and other transects as, in general, the vegetation at the north transect was similar to the other transects. Calcium uptake could also be responsible for similar decreases of calcium-silicon ratios at the other transects. The 50 cm depth calcium-silicon ratios at UF2 and F1 (the two peat sampling points closest to the upland) were statistically similar at the north transect but were statistically different in the middle and south transects (Table 11).

The reason for smaller – albeit not significantly smaller – calcium-silicon ratios at the 20-cm piezometers (particularly at the UF2 and F1 piezometers) at the north and middle transects may be linked to calcium uptake by vegetation or - seemingly less plausible based on stable hydraulic gradient data - some alternate groundwater flow path. It is possible that the 20-cm piezometers, because they are shallower, had less of a connection with the groundwater moving through the fen at deeper peat depths and thus these shallower measurements had smaller calcium concentrations. Precipitation additions to pore water near the surface could also dilute calcium concentrations. Another potential explanation was the presence of the shallow root zone in the top 20 cm, resulting in greater calcium uptake and lower concentrations relative to the 50 cm depth (Bedford and Godwin, 2003).

At all transects, similar patterns of decreasing calcium-silicon ratios were observed from nested piezometers UF1 to F3 progressing from the upland to the interior of the fen (Figure 13). However these ratios were generally smaller at the north transect. The general trend of decreasing calcium-silicon ratios in the boundary zone showed that the fen does not have a homogenous chemical pattern. The lower calcium-silicon ratios at the northern transect indicated that while each transect exhibited general patterns of decreasing calcium-silicon ratios, the ratios themselves were not the same in all areas of the fen. Lower calcium-silicon ratios at the north transect could signal a greater influence from upland near surface and subsurface stormflow from soil pore water than observed at the middle and southern transects.

Despite significant statistical differences between the transects, visual examination of average calcium-silicon ratios at each piezometer for all three transects (Figure 13) indicated that there was a similar pattern among locations in the fen: all three transects show that calcium-silicon ratios remain highest near the point of contact between the fen and the upland soils - specifically the UF1 piezometer where water was collected from mineral soil overlain by peat – followed by a general decrease in calcium-silicon ratios farther toward the interior of the fen. Potentially, water from mineral soil at the UF1 piezometer received minimal influence from diluting subsurface stormflow of the upland as well as minimal vegetative effects on calcium and therefore had high calcium concentrations from groundwater moving through the fen.

Since there was no statistical difference between the 20-cm U1 and UF2 piezometers or between the 20-cm UF2 and F1 piezometers at the middle transect, it was possible that upland subsurface flow contributions have an effect on shallow peat pore water all the way to F1. The middle transect 50 cm depth calcium-silicon ratios in the F1, F2, and F3 piezometers (Figure 13) were similar to the calcium-silicon ratios in the outlet of the S3 fen (Figure 16), as ANOVA testing resulted in a p-value of 0.534. Further, middle transect 50 cm depth calcium-silicon ratios in the F1, F2, and F3 piezometers were similar to mean S3 fen pore water calcium-silicon ratio of 3.39 (based on annual average flow-weighted mean of entire fen watershed) (Boelter and Verry, 1977). The south transect 50-cm F1 piezometer also had calcium-silicon ratios similar to that at the outlet ($p = 0.340$). Therefore, 50-cm peat pore water around the F1 piezometer (and beyond for the middle transect) appeared to be subject to similar ecological processes that influence chemistry as water leaving the fen at the outlet.

At the southern transect, calcium-silicon ratios were significantly greater in the 20-cm than the 50-cm for the F3 piezometer ($p = 7.52*10^{-9}$). These higher 20-cm calcium-ratios did not occur at the north and middle transects. A possible explanation was the proximity of the southern transect to the surface water outlet of the fen: Near the outlet at the south transect, the calcium-rich groundwater present at 20-cm depths would be similar to those at 50-cm depths at the north transect, as the surface and groundwater hydraulic head measurements are at the same level.

The significant differences in calcium-silicon ratio between piezometers F1 and F2 at the 50 cm depth for the north transect and between UF2 and F1 at the middle transect (Table 11) indicated some type of source water-chemical limit to the boundary zone based on decreasing calcium concentrations. This decrease in calcium potentially was caused by the presence of large trees such as tamarack and spruce at F2 that could cause increased calcium uptake (Glaser, 1990; Likens, 2013). While tree species are known to consume silicon (Cornelis et al., 2010), that does not appear to be a factor since silicon concentrations were fairly invariant. The similarity of pore water between F2 and F3 50-cm piezometers at the north and middle transect also indicated a uniform chemical pattern after this F1/F2 extent of the boundary zone was passed. The existence of the fen-upland boundary was further reinforced by the calcium-silicon ratios at F1 piezometers in the south and F1, F2 and F3 piezometers in the middle transect demonstrating similarity to calcium-silicon measurements at the fen outlet. Peat pore water at the 50-cm middle transect F1, F2, and F3 piezometers and the 50-cm south transect F1 piezometer were more similar to water that has traveled through the fen and was exiting the outlet than to UF1 and UF2 50-cm pore water. This F1/F2 site boundary therefore not only represents the initial influence of large tree species on pore water calcium-silicon ratios, but also an end to any type of observable influence on peat pore water chemistry from the upland surface and subsurface stormflow.

Concentrations of calcium and silicon in precipitation were very low in comparison to pore water concentrations (Figure 17). Calcium concentrations ranged from 0.02 mg L^{-1} to 2.96 mg L^{-1} with a mean of 0.54 mg L^{-1}. Silicon concentrations ranged from 0.00 mg L^{-1} to 0.22 mg L^{-1} with a mean of 0.04 mg L^{-1}. Precipitation calcium-silicon ratios had a mean of 19.96 because of the large differences between calcium and silicon concentrations. Despite these large calcium-silicon ratios, the small actual concentrations of calcium meant that precipitation could have mixed with groundwater to dilute pore water concentrations, particularly closer to the surface. Calcium concentrations in the stream were similar to those of most of the fen data between UF2 and F3 (Figure 17). Concurrently, calcium concentrations from the UF1 nested piezometers of the south and middle transects were higher than those from the stream (Figure 17). At the UF1 piezometers groundwater was in mineral soil and thus could be affected to a lesser extent by ecological processes and calcium concentrations may originate directly from groundwater moving through the fen. Ecological processes may be influencing peat pore water calcium concentrations and were thus reflected in smaller calcium-silicon ratios observed in the fen outlet stream.

End member analysis (Mulholland, 1993), indicated that calcium concentrations from the S3 stream outlet were bound by calcium concentrations at the F2 and F3 piezometers and by the mineral soil piezometers of UF1 (Figure 17). This suggests that surface water leaving the fen was influenced by groundwater that was present at the UF1 piezometers and within the boundary zone in general as well as water that moves through the peat soils at the F2 and F3 piezometers. This contrasts with bogs, where stream water chemistry is largely influenced by flow moving through the bog boundary zone (Kolka et al., 2011).

Conclusions

Calcium-silicon ratios decreased from mineral soil pore water at the edge of the fen (UF1) to the interior of the fen (F3). Decreases in calcium-silicon ratios were particularly noticeable at F1 in the middle transect and F2 in the northern transect - often where large peatland tree species began - marking the limit of the zone of influence from uplands waters and demarcating the end to the boundary zone of the fen. Local variations in calcium-silicon ratio (such as that at the high 20-cm F3 nested piezometer in the southern transect) coupled with changes in vegetation among transects indicated a complex series of ecological and perhaps hydrological processes which expands upon general fen chemistry data like that determined by Boelter and Verry (1977). Vegetative calcium uptake was one possible explanation for this pattern. The change in pore water chemistry in the fen-upland boundary zone is important to better understand the unique ecological environment in fens.

Calcium-silicon ratios at the U1 piezometers were generally lower than those at the UF1 piezometers and showed that the upland near surface or shallow subsurface stormflow does not have a strong chemical influence on the rest of the piezometers. Strong upland influence would be characterized by calcium-silicon ratios at the UF1 nested piezometer that closely match those at the U1 nested piezometer (as water flowed downward and toward the fen through the subsurface between UF1 and U1), with corresponding increases in calcium-silicon ratios at the UF2 nested piezometer because of greater distance from the upland influence.

Future studies of the upland zone of influence should attempt to focus on processes causing changes in calcium concentration at each nested piezometer location. For example, investigation of specific plant physiology in terms of calcium uptake would determine the role of ecological processes in fen calcium concentration and therefore calcium-silicon ratios. With such a study, it would be possible to link forest biological processes with changes in peat pore water chemistry. Furthermore, additional studies could measure peat pore water across a greater area of the fen and include samples from deeper groundwater within the fen watershed, which would help determine spatial changes in chemistry of the entire fen.

ILLUSTRATIONS – Chapter 2

Table 7: Calcium concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date												
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep	MEAN
North	U1 - 20 cm													n/a
North	UF2 - 20 cm	13.21	13.43	13.28	13.21	14.58	14.42	13.21		14.03	13.45	11.87	13.01	13.43
North	F1 - 20 cm	8.13	8.35	8.89	7.96	9.96	9.44	8.94	8.88	8.79	7.72	7.93	8.40	8.62
North	F2 - 20 cm	8.75	8.54	9.28	9.30	10.26	10.70	9.76	10.04	10.36	9.97	9.62	9.84	9.70
North	F3 - 20 cm	9.97	9.00	8.52	8.62	10.07	9.25	9.42	9.94	9.85	9.82	9.88	9.82	9.51
North	U1 - 50 cm	14.61		14.51	16.64	17.73	18.14	16.81	18.75	19.74		21.12	21.38	17.94
North	UF1 - 50 cm		23.27	25.48	28.64	25.27	25.63	24.99	26.20	25.44	25.65	24.93	25.99	25.59
North	UF2 - 50 cm	23.28	24.47	24.36	25.89	23.27	23.47	22.64	22.82	22.81	22.38	21.86	21.91	23.26
North	F1 - 50 cm	22.50	19.19	21.63	19.56	20.53	19.85	19.77	20.61	21.32	20.69	21.05	21.48	20.68
North	F2 - 50 cm	12.60	13.49	11.52	11.63	11.88	11.98	11.41	11.79	11.88	11.86	11.57	11.70	11.94
North	F3 - 50 cm	12.35	13.23	10.09	9.43	12.51	11.26	9.26	12.33	12.24	12.49	11.87	11.41	11.54
North	UF1 - 70 cm				25.82	29.38	30.64	28.44	30.16	29.79	28.71	27.56	26.21	28.52
Middle	U1 - 20 cm				19.71			17.91				18.10		18.57
Middle	UF2 - 20 cm	32.93	32.93	34.06	34.74	40.53	37.21	36.03	34.80	32.11	29.87	35.09	37.03	34.78
Middle	F1 - 20 cm	31.94	36.34	34.95	38.82	36.38	37.44	35.91	38.66	37.27	38.46	34.89	34.18	36.27
Middle	F2 - 20 cm	23.44	23.71	22.50	23.60	25.78	26.25	25.18	26.04	27.08	27.26	27.01	27.84	25.47
Middle	F3 - 20 cm	19.51	20.17	20.45	22.13	24.62	24.39	21.80	22.81	22.56	23.07	23.41	24.72	22.47
Middle	U1 - 50 cm	28.28	32.44	31.79	38.31	35.98	36.38	38.33	39.83	39.82	41.07	42.43	42.51	37.26
Middle	UF1 - 50 cm		54.29	59.19	68.61	55.74	55.58	52.94	54.29	52.95	52.91	51.52	51.22	55.39
Middle	UF2 - 50 cm	52.09	55.42	51.70	52.47	52.84	53.91	52.57	54.26	55.02	54.87	54.00	54.51	53.64
Middle	F1 - 50 cm	49.43	51.36	44.66	43.73	48.90	49.62	47.83	42.98	50.52	50.20	49.30	50.30	48.24
Middle	F2 - 50 cm	38.10	38.58	32.10	35.00	37.99	39.46			39.95	38.13	36.29	37.63	37.32
Middle	F3 - 50 cm	37.26	38.28	33.17	35.36	36.76	37.17	33.96	38.73	39.47	38.70	37.17	39.02	37.09
Middle	UF1 - 70 cm		55.93	55.33	52.74	54.77	54.43	52.78	53.77	52.81	52.44	52.22	52.10	53.57
South	U1 - 20 cm													n/a
South	UF2 - 20 cm	12.29	12.57	12.94	11.04	19.35	18.68	15.04	16.93	16.61	16.69	16.39	16.69	15.44
South	F1 - 20 cm	12.63	13.82	14.48	16.72	19.06	18.21	18.15	18.67	19.43	19.51	19.49	20.37	17.55
South	F2 - 20 cm	13.08	13.84	17.90	17.98	21.98	18.79	16.78	18.33	18.58	18.24	17.97	18.75	17.69
South	F3 - 20 cm	15.98	18.51	19.31	22.11	24.71	23.53	24.95	24.37	24.89	25.05	25.51	26.53	22.95
South	U1 - 50 cm													n/a
South	UF1 - 50 cm			45.22			48.04							46.63
South	UF2 - 50 cm	26.71	29.48	26.77	25.61	29.42	28.56	28.40	30.86	30.11	29.31	29.05	29.41	28.64
South	F1 - 50 cm	35.09	35.15	33.82	33.02	36.62	34.02	34.43	37.17	36.65	36.11	34.71	34.10	35.07
South	F2 - 50 cm	15.37	13.45	14.55	16.82	19.86	19.68	19.28	19.55	19.65	18.80	19.07	20.36	18.04
South	F3 - 50 cm	18.59	15.59	11.87	15.75	18.70	17.99	13.95	18.58	18.86	18.02	17.68	17.23	16.90
South	UF1 - 70 cm													n/a

T**able 8:** Silicon concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date												
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep	MEAN
North	U1 - 20 cm													n/a
North	UF2 - 20 cm	16.19	15.51	14.25	13.04	14.06	14.42	13.42		13.70	14.78	12.64	13.05	14.10
North	F1 - 20 cm	7.10	8.70	7.69	7.35	7.80	8.30	8.42	8.79	9.10	9.59	9.37	9.45	8.47
North	F2 - 20 cm	9.09	9.53	9.53	9.13	8.70	9.05	9.13	9.79	10.01	10.41	10.61	10.65	9.63
North	F3 - 20 cm	10.48	10.25	9.81	10.04	9.87	10.82	10.71	11.34	11.66	11.90	11.46	11.64	10.83
North	U1 - 50 cm	25.95		11.79	12.20	12.45	12.58	12.87	13.28	14.09		14.60	14.45	14.43
North	UF1 - 50 cm		14.26	11.45	14.42	12.25	12.50	12.40	12.79	12.52	12.72	12.75	12.65	12.79
North	UF2 - 50 cm	14.79	14.39	13.72	14.48	12.26	12.85	12.34	12.66	12.72	12.75	12.69	12.68	13.19
North	F1 - 50 cm	13.79	11.97	13.21	11.03	11.09	11.12	11.36	11.46	11.56	11.85	11.45	11.16	11.75
North	F2 - 50 cm	12.58	13.70	11.93	11.10	11.73	11.87	11.42	11.93	11.91	11.77	11.54	11.56	11.92
North	F3 - 50 cm	12.71	12.77	11.66	11.57	12.27	12.26	12.09	12.42	12.48	12.57	11.87	11.77	12.20
North	UF1 - 70 cm				13.91	11.69	11.79	11.69	11.82	12.19	12.10	11.71	11.79	12.08
Middle	U1 - 20 cm				4.57			5.24				5.34		5.05
Middle	UF2 - 20 cm	8.58	8.66	7.79	8.24	8.61	9.26	9.42	9.69	10.16	10.64	9.52	9.70	9.19
Middle	F1 - 20 cm	9.54	11.63	9.59	11.17	10.01	10.12	10.19	10.48	10.61	10.70	10.45	10.40	10.41
Middle	F2 - 20 cm	9.13	9.58	8.22	8.86	9.62	10.08	10.00	10.32	10.52	10.75	10.52	10.54	9.84
Middle	F3 - 20 cm	7.79	8.43	7.67	9.40	9.89	10.14	9.91	10.33	10.65	11.17	10.71	10.71	9.73
Middle	U1 - 50 cm	7.94	8.78	7.78	10.54	7.83	7.70	7.83	7.95	8.09	8.05	7.99	8.08	8.21
Middle	UF1 - 50 cm		8.03	7.57	9.45	8.21	8.49	8.26	8.22	8.24	8.29	7.92	8.08	8.25
Middle	UF2 - 50 cm	8.38	8.94	7.98	8.02	8.03	8.22	7.89	8.15	8.37	8.43	7.98	8.04	8.20
Middle	F1 - 50 cm	10.97	11.68	9.23	8.92	10.35	10.26	10.12	10.12	10.29	10.39	9.93	9.92	10.18
Middle	F2 - 50 cm	12.14	11.63	9.54	10.25	10.78	10.73			10.83	10.79	10.39	10.23	10.73
Middle	F3 - 50 cm	11.20	11.85	10.10	10.43	10.66	10.66	10.74	10.85	11.00	11.02	10.76	10.75	10.84
Middle	UF1 - 70 cm		7.52	6.95	9.30	7.34	7.39	7.20	7.40	8.99	7.56	7.27	7.36	7.66
South	U1 - 20 cm													n/a
South	UF2 - 20 cm	5.34	6.16	5.97	5.73	7.00	7.21	6.68	7.12	7.41	7.82	7.58	7.59	6.80
South	F1 - 20 cm	5.35	6.03	5.64	6.72	7.18	7.21	7.41	7.53	7.60	7.32	7.76	8.10	6.99
South	F2 - 20 cm	4.99	6.23	6.76	7.04	7.26	7.26	7.69	8.48	9.28	9.52	9.66	10.42	7.88
South	F3 - 20 cm	5.00	5.98	6.57	7.62	8.71	8.63	9.16	9.58	10.17	10.16	10.18	10.17	8.49
South	U1 - 50 cm													n/a
South	UF1 - 50 cm			5.45			6.34							5.90
South	UF2 - 50 cm	11.02	12.01	10.74	8.27	11.49	10.93	11.41	11.67	11.44	11.16	10.73	10.99	10.99
South	F1 - 50 cm	9.44	10.20	8.39	8.68	9.46	9.10	8.68	8.86	9.11	8.59	8.63	9.14	9.02
South	F2 - 50 cm	6.10	5.69	7.03	6.80	7.65	7.61	7.99	8.24	8.58	8.70	8.95	9.33	7.72
South	F3 - 50 cm	9.07	8.34	9.96	8.40	9.09	8.98	8.98	9.43	9.74	9.55	9.40	9.37	9.19
South	UF1 - 70 cm													n/a

Table 9: Calcium-silicon ratios at each piezometer location for all data collection days.

		Date												
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep	MEAN
North	U1 - 20 cm													n/a
North	UF2 - 20 cm	0.82	0.87	0.93	1.01	1.04	1.00	0.98		1.02	0.91	0.94	1.00	0.96
North	F1 - 20 cm	1.15	0.96	1.16	1.08	1.28	1.14	1.06	1.01	0.97	0.81	0.85	0.89	1.03
North	F2 - 20 cm	0.96	0.90	0.97	1.02	1.18	1.18	1.07	1.03	1.03	0.96	0.91	0.92	1.01
North	F3 - 20 cm	0.95	0.88	0.87	0.86	1.02	0.85	0.88	0.88	0.85	0.83	0.86	0.84	0.88
North	U1 - 50 cm	0.56		1.23	1.36	1.42	1.44	1.31	1.41	1.40		1.45	1.48	1.31
North	UF1 - 50 cm		1.63	2.23	1.99	2.06	2.05	2.02	2.05	2.03	2.02	1.96	2.05	2.01
North	UF2 - 50 cm	1.57	1.70	1.78	1.79	1.90	1.83	1.83	1.80	1.79	1.76	1.72	1.73	1.77
North	F1 - 50 cm	1.63	1.60	1.64	1.77	1.85	1.79	1.74	1.80	1.84	1.75	1.84	1.92	1.76
North	F2 - 50 cm	1.00	0.98	0.97	1.05	1.01	1.01	1.00	0.99	1.00	1.01	1.00	1.01	1.00
North	F3 - 50 cm	0.97	1.04	0.87	0.82	1.02	0.92	0.77	0.99	0.98	0.99	1.00	0.97	0.94
North	UF1 - 70 cm				1.86	2.51	2.60	2.43	2.55	2.44	2.37	2.35	2.22	2.37
Middle	U1 - 20 cm				4.31			3.42				3.39		3.71
Middle	UF2 - 20 cm	3.84	3.80	4.37	4.22	4.71	4.02	3.82	3.59	3.16	2.81	3.69	3.82	3.82
Middle	F1 - 20 cm	3.35	3.12	3.64	3.48	3.63	3.70	3.52	3.69	3.51	3.59	3.34	3.29	3.49
Middle	F2 - 20 cm	2.57	2.47	2.74	2.66	2.68	2.60	2.52	2.52	2.57	2.54	2.57	2.64	2.59
Middle	F3 - 20 cm	2.51	2.39	2.67	2.35	2.49	2.41	2.20	2.21	2.12	2.07	2.19	2.31	2.33
Middle	U1 - 50 cm	3.56	3.70	4.09	3.63	4.60	4.73	4.89	5.01	4.92	5.11	5.31	5.26	4.57
Middle	UF1 - 50 cm		6.76	7.82	7.26	6.79	6.54	6.41	6.61	6.43	6.38	6.51	6.34	6.71
Middle	UF2 - 50 cm	6.21	6.20	6.48	6.54	6.58	6.56	6.66	6.66	6.57	6.51	6.77	6.78	6.54
Middle	F1 - 50 cm	4.51	4.40	4.84	4.90	4.72	4.84	4.73	4.25	4.91	4.83	4.97	5.07	4.75
Middle	F2 - 50 cm	3.14	3.32	3.37	3.41	3.52	3.68			3.69	3.53	3.49	3.68	3.48
Middle	F3 - 50 cm	3.33	3.23	3.28	3.39	3.45	3.49	3.16	3.57	3.59	3.51	3.45	3.63	3.42
Middle	UF1 - 70 cm		7.43	7.96	5.67	7.46	7.36	7.33	7.26	5.87	6.94	7.18	7.07	7.05
South	U1 - 20 cm													n/a
South	UF2 - 20 cm	2.30	2.04	2.17	1.93	2.76	2.59	2.25	2.38	2.24	2.14	2.16	2.20	2.26
South	F1 - 20 cm	2.36	2.29	2.57	2.49	2.66	2.53	2.45	2.48	2.56	2.67	2.51	2.51	2.51
South	F2 - 20 cm	2.62	2.22	2.65	2.55	3.03	2.59	2.18	2.16	2.00	1.92	1.86	1.80	2.30
South	F3 - 20 cm	3.20	3.10	2.94	2.90	2.84	2.73	2.72	2.55	2.45	2.47	2.51	2.61	2.75
South	U1 - 50 cm													n/a
South	UF1 - 50 cm			8.29			7.58							7.93
South	UF2 - 50 cm	2.42	2.45	2.49	3.10	2.56	2.61	2.49	2.64	2.63	2.63	2.71	2.68	2.62
South	F1 - 50 cm	3.72	3.45	4.03	3.80	3.87	3.74	3.97	4.20	4.02	4.20	4.02	3.73	3.90
South	F2 - 50 cm	2.52	2.36	2.07	2.47	2.60	2.59	2.41	2.37	2.29	2.16	2.13	2.18	2.35
South	F3 - 50 cm	2.05	1.87	1.19	1.88	2.06	2.00	1.55	1.97	1.94	1.89	1.88	1.84	1.84
South	UF1 - 70 cm													n/a

Table 10: Hydraulic head data (meters above sea level) at each piezometer location for all data collection days. Note that empty entries in the table represent days when the water table was below the bottom of a piezometer.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm												
North	UF2 - 20 cm	413.86	413.88	413.86	413.86	413.84	413.80	413.84	413.82	413.79	413.75	413.82	413.81
North	F1 - 20 cm	413.86	413.89	413.86	413.87	413.85	413.81	413.85	413.83	413.80	413.78	413.82	413.88
North	F2 - 20 cm	413.85	413.87	413.86	413.85	413.82	413.78	413.83	413.82	413.78	413.77	413.82	413.83
North	F3 - 20 cm	413.90	413.92	413.91	413.91	413.89	413.85	413.87	413.82	413.81	413.78	413.82	413.84
North	U1 - 50 cm	413.87		413.84	413.88	413.94	413.79	413.84	413.72	413.68		413.72	413.71
North	UF1 - 50 cm		413.49	413.91	413.91	413.89	413.83	413.87	413.77	413.76	413.71	413.79	413.79
North	UF2 - 50 cm	413.86	413.89	413.84	413.85	413.83	413.80	413.83	413.81	413.79	413.76	413.82	413.81
North	F1 - 50 cm	413.85	413.86	413.87	413.88	413.85	413.81	413.85	413.83	413.80	413.78	413.83	413.84
North	F2 - 50 cm	413.87	413.89	413.87	413.86	413.84	413.81	413.85	413.82	413.80	413.77	413.83	
North	F3 - 50 cm	413.91	413.94	413.90	413.90	413.88	413.85	413.88	413.82	413.80	413.76	413.82	413.84
North	UF1 - 70 cm				413.40	413.74	413.65	413.65	413.65	413.56	413.49	413.62	413.59
Middle	U1 - 20 cm				412.90			412.90				412.87	
Middle	UF2 - 20 cm	412.85	412.86	412.82	412.84	412.80	412.78	412.83	412.78	412.77	412.75	412.79	412.86
Middle	F1 - 20 cm	412.83	412.88	412.84	412.86	412.81	412.78	412.82	412.77	412.77	412.75	412.80	412.86
Middle	F2 - 20 cm	412.84	412.87	412.82	412.82	412.80	412.78	412.81	412.76	412.76	412.65	412.79	412.84
Middle	F3 - 20 cm	412.81	412.85	412.82	412.82	412.79	412.78	412.81	412.77	412.76	412.75	412.79	412.84
Middle	U1 - 50 cm	412.82	412.87	412.82	412.82	412.77	412.77	412.81	412.73	412.72	412.72	412.76	412.85
Middle	UF1 - 50 cm		412.88	412.85	412.88	412.81	412.78	412.83	412.77	412.75	412.74	412.80	412.87
Middle	UF2 - 50 cm	412.80	412.84	412.79	412.79	412.76	412.74	412.79	412.77	412.76	412.75	412.80	412.86
Middle	F1 - 50 cm	412.85	412.88	412.84	412.82	412.80	412.78	412.83	412.78	412.78	412.76	412.81	412.87
Middle	F2 - 50 cm	412.78	412.83	412.78	412.79	412.76	412.74			412.76	412.73	412.80	412.85
Middle	F3 - 50 cm	412.82	412.87	412.77	412.82	412.79	412.78	412.81	412.77	412.76	412.75	412.80	412.85
Middle	UF1 - 70 cm		412.80	412.84	412.83	412.80	412.79	412.83	412.76	412.74	412.74	412.78	412.87
South	U1 - 20 cm												
South	UF2 - 20 cm	412.63	412.66	412.58	412.41	412.59	412.56	412.58	412.53	412.51	412.50	412.52	412.54
South	F1 - 20 cm	412.59	412.65	412.58	412.40	412.57	412.55	412.58	412.54	412.52	412.51	412.53	412.59
South	F2 - 20 cm	412.60	412.63	412.59	412.40	412.56	412.55	412.57	412.52	412.52	412.50	412.53	412.58
South	F3 - 20 cm	412.52	412.57	412.51	412.32	412.50	412.48	412.50	412.49	412.47	412.44	412.47	412.52
South	U1 - 50 cm												
South	UF1 - 50 cm			412.11	412.08	412.23	412.14						
South	UF2 - 50 cm	412.46	412.66	412.59	412.41	412.57	412.55	412.58	412.53	412.51	412.50	412.53	412.54
South	F1 - 50 cm	412.60	412.64	412.59	412.41	412.57	412.55	412.57	412.53	412.52	412.51	412.53	412.59
South	F2 - 50 cm	412.59	412.62	412.57	412.39	412.55	412.54	412.57	412.53	412.52	412.50	412.53	412.58
South	F3 - 50 cm	412.59	412.62	412.58	412.41	412.56	412.54	412.57	412.54	412.53	412.52	412.54	412.59
South	UF1 - 70 cm												

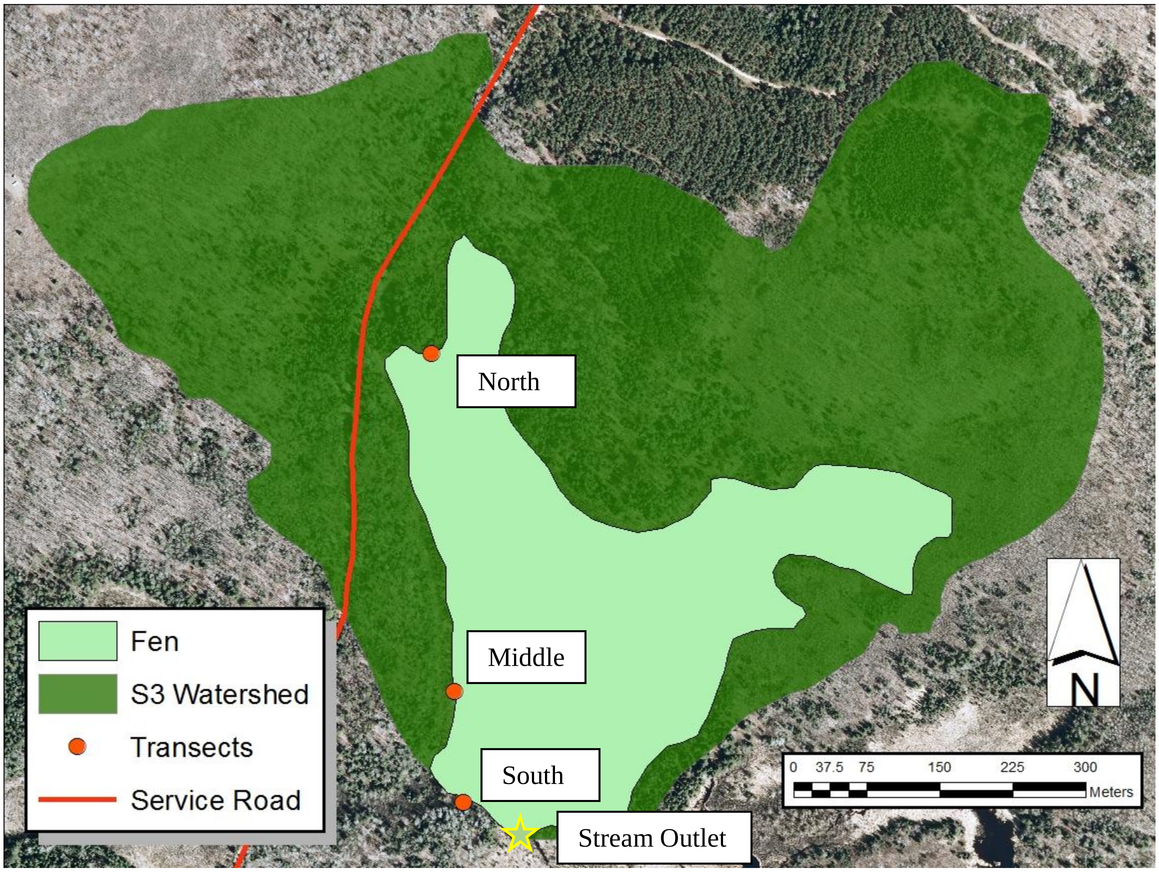
Table 11: Statistical differences for Ca:Si between piezometer locations for each transect based on a pairwise t-test with the p-value determined with the Bonferroni method.

Transect	U1-UF1 (for 50 cm)/U1-UF2 (for 20 cm)	UF1-UF2	UF2-F1	F1-F2	F2-F3
North – 20 cm	n/a	n/a	0.439	1.000	0.011
North – 50 cm	< 0.001	< 0.001	1.000	< 0.001	1.000
Middle – 20 cm	1.000	n/a	0.093	< 0.001	0.368
Middle – 50 cm	< 0.001	1.000	< 0.001	< 0.001	1.000
South – 20 cm	n/a	n/a	0.164	0.342	< 0.001
South – 50 cm	n/a	< 0.001	< 0.001	< 0.001	< 0.001

Table 12: Repeated measures ANOVA and pairwise t-test p-values for calcium-silicon ratios at each data collection time. The "Repeated ANOVA" row shows results from the repeated measures ANOVA test. A significant p-value ($p < 0.05$) here means that, for each piezometer, at least one of the transects is statistically different from the at least one of the others. The pairwise t-test results in the "North-Middle," "North-South," and "Middle-South" rows show which transects are statistically different from one another at $p < 0.05$.

	Significance Teset (p-values)			
Date	**Repeated ANOVA**	**North-Middle**	**North-South**	**Middle-South**
6-18	< 0.0001	< 0.0001	0.0089	0.0006
6-22	< 0.0001	< 0.0001	0.0270	0.0010
7-2	< 0.0001	< 0.0001	0.0104	0.0011
7-12	< 0.0001	< 0.0001	0.0132	0.0042
7-27	< 0.0001	< 0.0001	0.0007	0.0019
8-3	< 0.0001	< 0.0001	0.0009	0.0009
8-9	< 0.0001	< 0.0001	0.0032	0.0064
8-17	< 0.0001	< 0.0001	0.0008	0.0092
8-22	< 0.0001	< 0.0001	0.0011	0.0017
8-27	< 0.0001	< 0.0001	0.0014	0.0017
9-6	< 0.0001	< 0.0001	0.0006	0.0014
9-12	< 0.0001	< 0.0001	0.0007	0.0014

Figure 10: Site map of the S3 fen and watershed in northern Minnesota, with the location of transects.



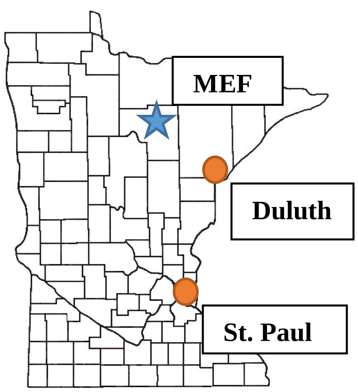


Figure 11: Transect organization and arrangement of multi-depth piezometer wells. Black piezometers are 20 cm/50 cm depth and the red piezometer is 50 cm/70 cm. As shown, the first two piezometers sampled water from mineral soil, while the third piezometer lies at the mineral soil/peat boundary and the last three piezometers sampled water from peat. Hypothetical water movement shown with blue arrows.

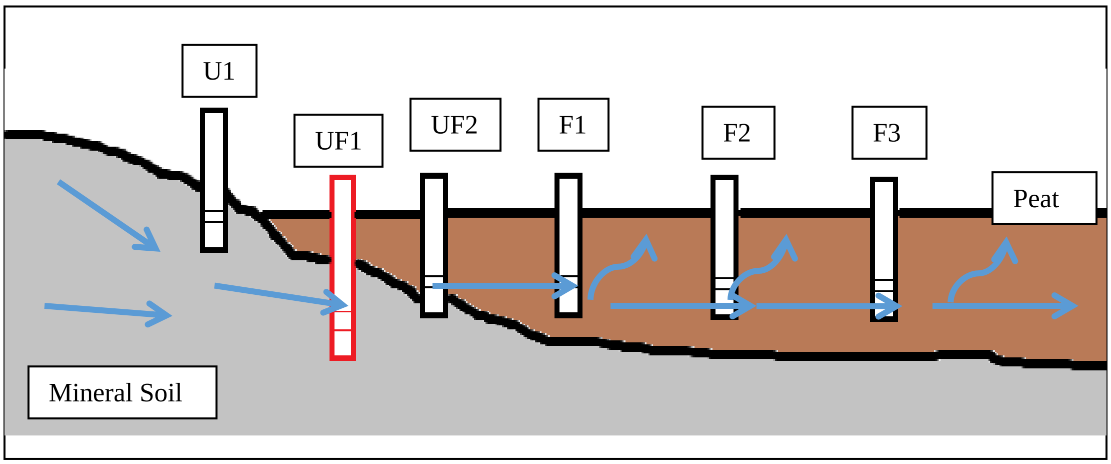
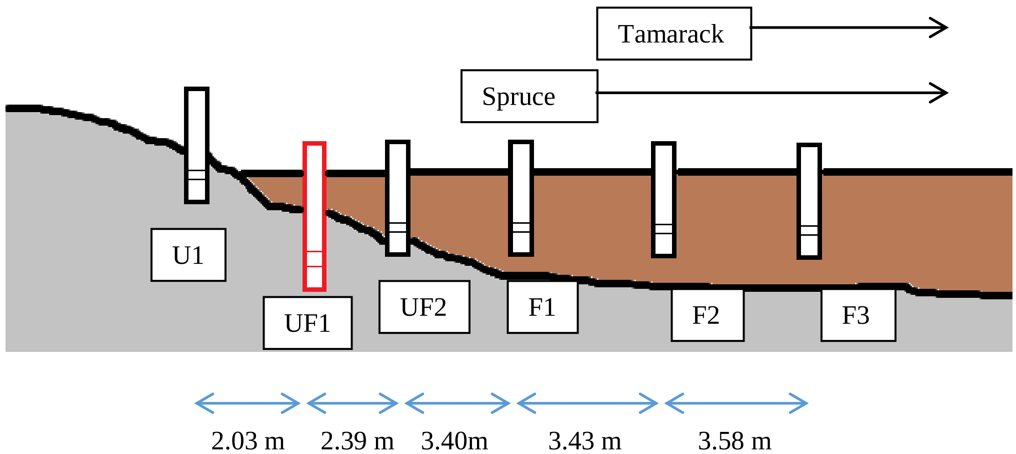
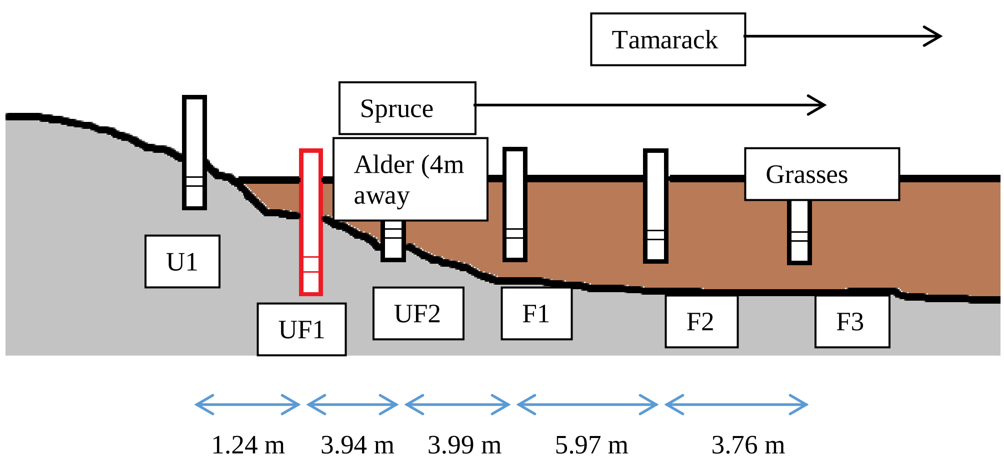


Figure 12: Distribution of vegetation at each transect. Black piezometers are 20 cm and 50 cm depth and the red piezometer is 50 cm and 70 cm. Blue arrow lines represent distances between adjacent piezometers. **a)** North transect. Length: 14.83 m; 0.31 m elevation difference between land surface at U1 and F3. **b)** Middle transect. Length: 18.90 m; 0.37 m elevation difference between land surface at U1 and F3. Note that the alder is approximately 4 meters from the transect. **c)** South transect. Length: 29.79 m; 0.67 m elevation difference between land surface at U1 and F3.

12a)



12b)



12c)

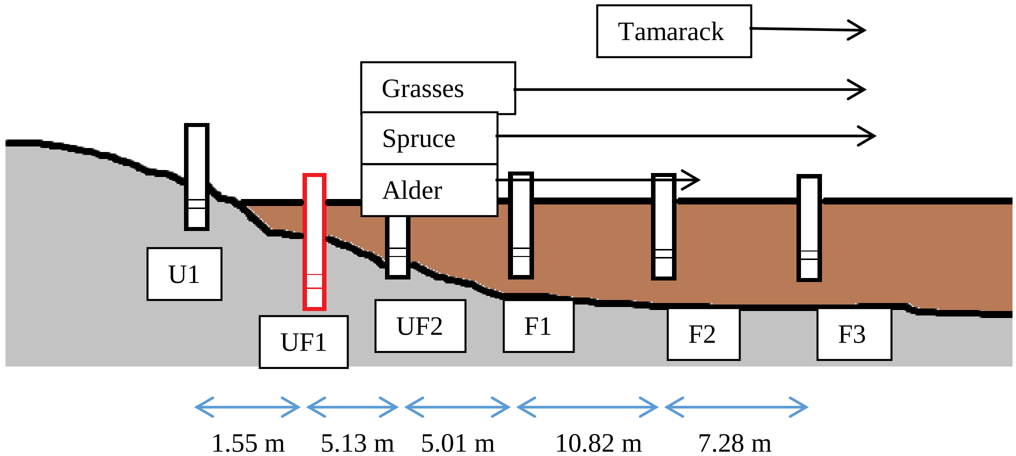

Tamarack
Grasses
Spruce
Alder
U1
UF1
UF2
F1
F2
F3
1.55 m
5.13 m
5.01 m
10.82 m
7.28 m

Figure 13: Box plot of calcium-silicon ratios. Red circles represent the mean of calcium-silicon ratios from each piezometer. Whiskers in this plot are the minimum and maximum values observed. Wide black lines divide data for different transects. Note that each horizontal column represents one nested piezometer with two depths and the dark black lines separate transects. For piezometer location labels, “N,” “M,” and “S” respresent north middle and south ransects and “20,” “50,” and “70” represent centimeter depth of piezometer.

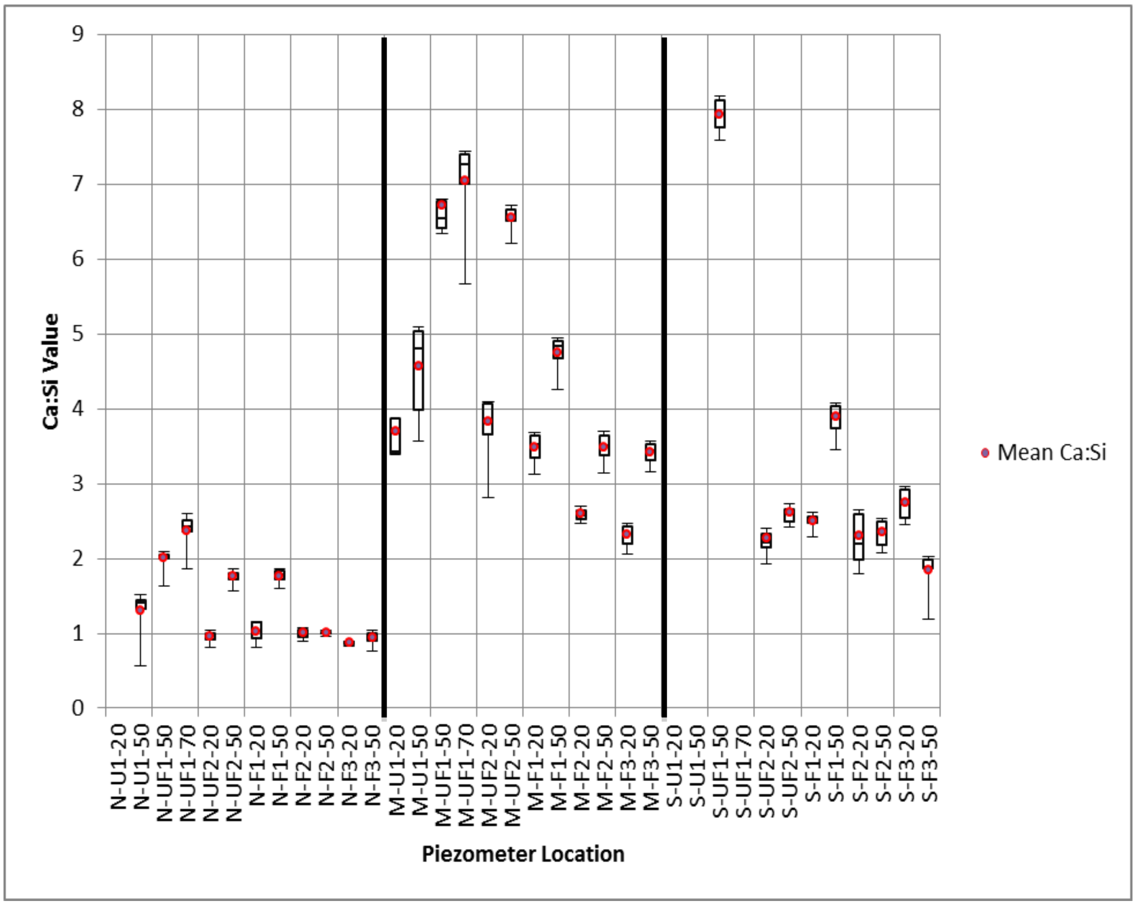


Figure 14: Box plot of hydraulic head. Hydraulic head readings were averaged for all dates available at each location. Whiskers in this plot are the minimum and maximum values observed. Wide black lines divide data for different transects. Note that each delineated column represents one nested piezometer with two depths and the dark black lines separate transects. For piezometer location labels, “N,” “M,” and “S” respresent north middle and south ransects and “20,” “50,” and “70” represent centimeter depth of piezometer.

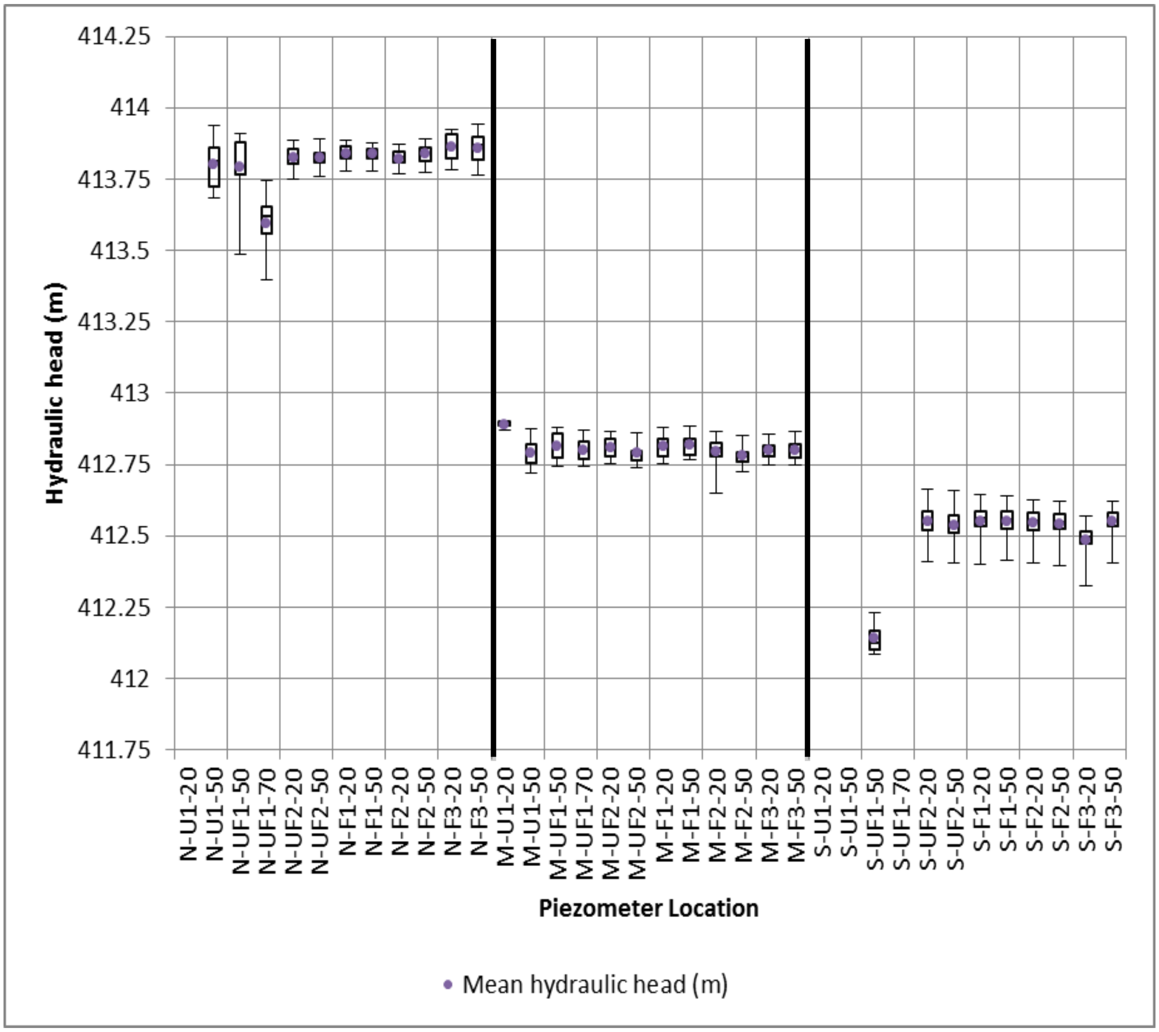


Figure 15: Example of hydraulic gradient and surface elevation from the northern transect on September 12th, 2013. Note the 55 cm distance between the 50-cm piezometer hydraulic gradient and the corresponding surface elevation at the U1 piezometer. This 55 cm is the zone of infiltration for surface and subsurface stormflow to the hydraulic gradient in the upland slope.

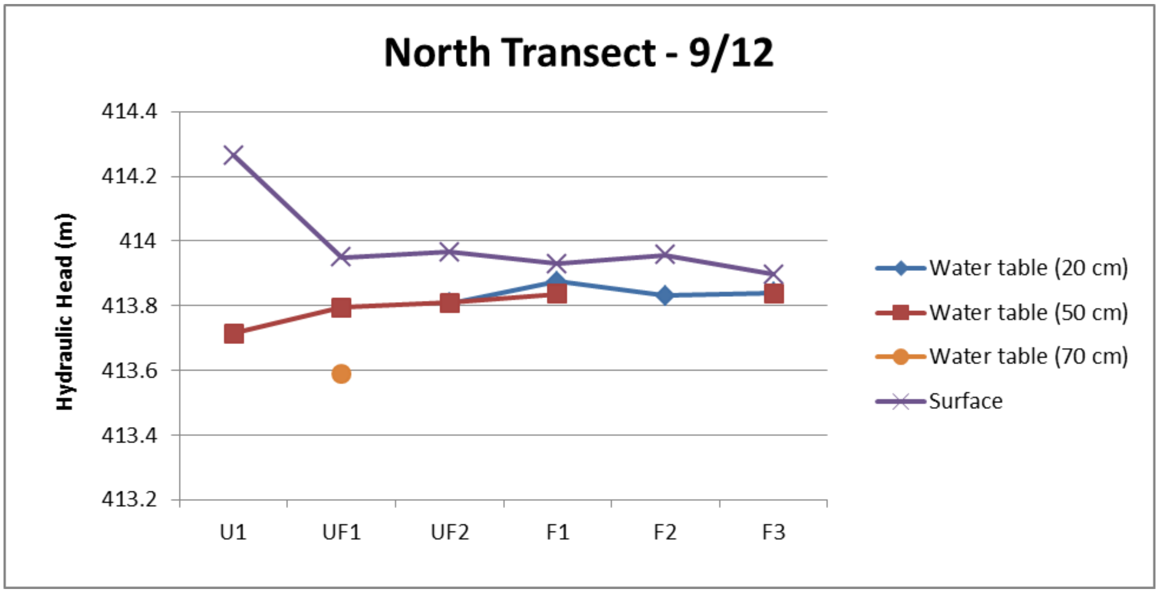


Figure 16: Observed calcium-silicon ratios at the outlet of S3 by day of year for June to September from biweekly sampling between 2009 and 2012. This range of ratios is similar to what is observed at the F1, F2 and F3 nested piezometer locations of the middle and southern transects.

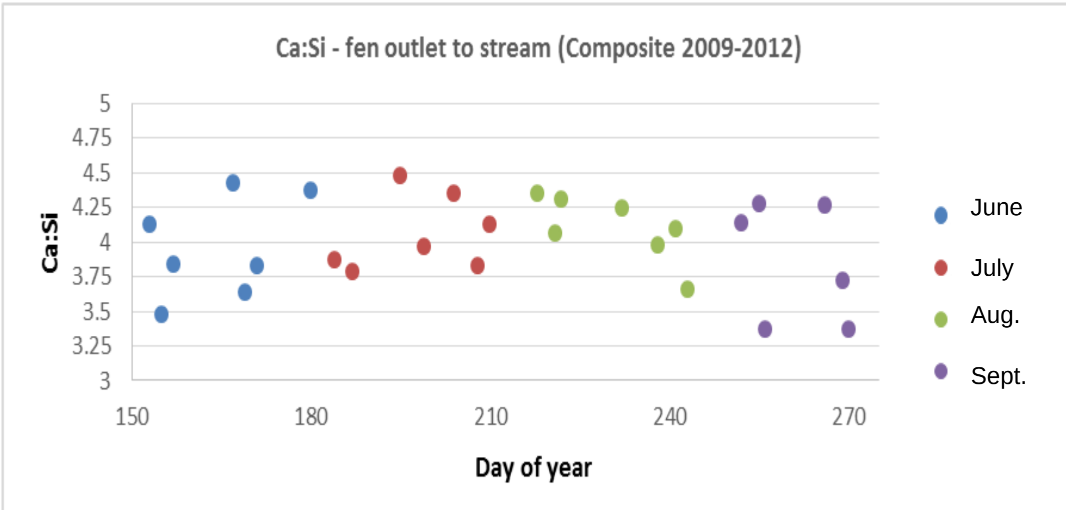
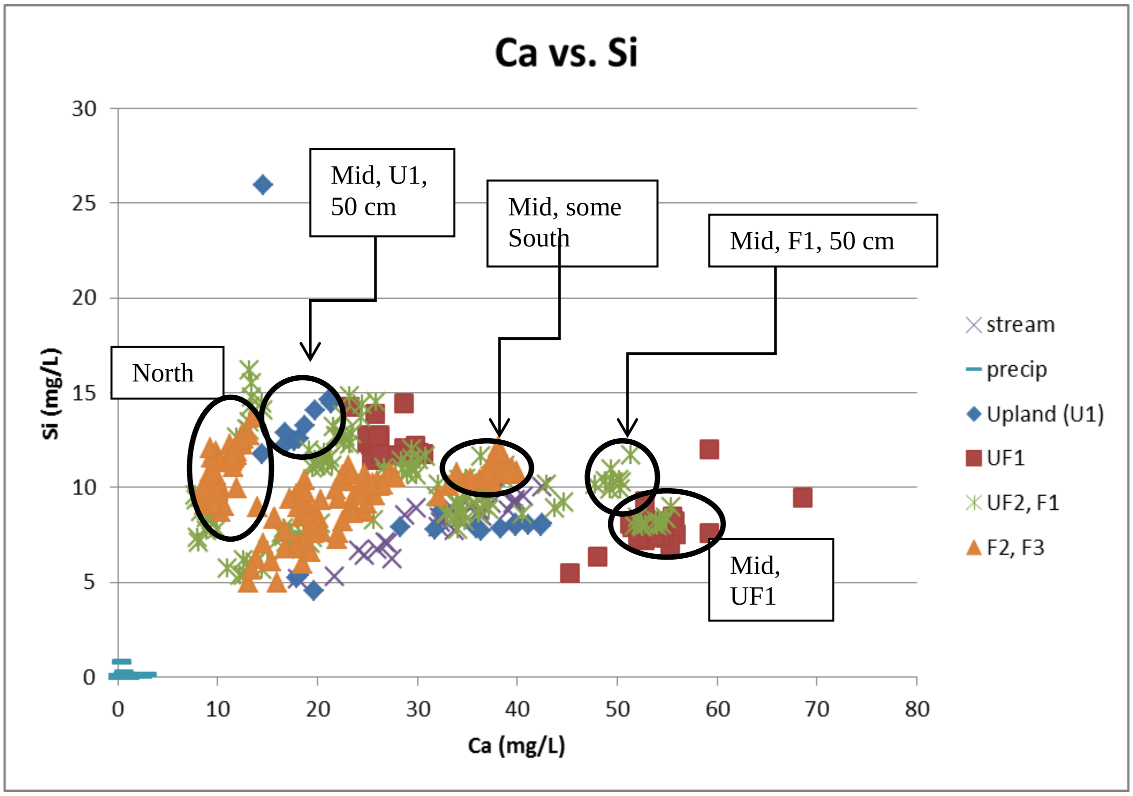


Figure 17: Bivariate plot of calcium and silicon data from pore waters, the S3 fen outlet stream, and local precipitation. Calcium concentrations from the stream are similar to a majority of those from peat pore water.



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APPENDIX

The following describes laboratory methods for chemical analyses of peat pore water samples not used in data analysis for this thesis including measuring the concentrations of aluminum, ammonium, dissolved organic carbon, iron, magnesium, manganese, nitrate-nitrite, ortho-phosphate, potassium, sodium, strontium, total nitrogen, and total phosphorus. Note that there is additional data present in these tables compared to calcium and silicon concentrations previously in the thesis because some unpurged wells are included. The unpurged data contains potentially stagnant water samples which may affect result in concentrations different than that in surrounding soils. This caveat should be included in any conclusions drawn from these data. Unpurged well dates and locations follow, with "N" representing the north transect, "M" the middle transect, and "S" the south transect: June 22 (M-U1-20cm); July 2 (M-U1-20cm); July 12 (N-U1-20cm, S-U1-20cm, S-U1-50cm, S-UF1-70cm); July 29 (N-U1-20cm, M-U1-20cm, S-U1-20cm, S-UF1-70cm); August 3 (N-U1-20cm, M-U1-20cm); August 9 (N-U1-20cm, S-U1-20cm, S-UF1-50cm); August 17 (N-U1-20cm, M-U1-20cm, S-UF1-50cm); August 22 (M-U1-20cm, S-U1-50cm, S-UF1-50cm); August 27 (S-UF1-50cm); September 6 (N-U1-20cm, S-UF1-50cm); September 12 (M-U1-20cm, S-U1-20cm, S-UF1-50cm, S-UF1-70cm).

Cation (aluminum, iron, magnesium, manganese, potassium, sodium, and strontium) concentrations were measured with Thermo Elemental Iris Intrepid inductively coupled plasma optical emission spectrometry (ICP-OES) according to Standard Method 3120 B methodology. Ammonium, nitrate-nitrite, ortho-phosphate, total nitrogen, and total phosphorus concentrations were measured with a Lachat QuikChem 8000 auto-analyzer. The limits of detection were: 0.02 mg ammonium-N/L (Lachat QuikChem method 10-107-06-1-C), 0.02 mg nitrate-N/L (Lachat QuikChem method 10-107-04-1-C), 0.001 mg phosphate-P/L ((Lachat QuikChem method 10-115-01-1-B), 0.05 mg total nitrogen/L (Lachat QuikChem method 10-107-04-1-P), and 0.05 mg total phosphorus/L (Lachat QuikChem method 10-115-01-3-A). Dissolved organic carbon concentrations was measured with a Shimazu TOC-VCP, requiring high temperature combustion (detection limit = 0.4 mg/L) according to Standard Method 5310 B (Inorganic, 2010). All chemical analysis was performed at the USDA Forest Service Laboratory in Grand Rapids, MN under the supervision of staff chemists.

Table 13: Aluminum concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.7643	1.141	0.7849	0.8142	0.6759			0.3916	
North	U1 - 50 cm	10.96		1.982	1.337	0.6323	0.3254	0.4035	0.3929	0.4449		0.2357	0.2162
North	UF1 - 50 cm		1.647	0.1226	0.1541	0	0.0402	0.0148	0	0	0	0	0
North	UF1 - 70 cm				0.8673	0.1776	0.105	0.1729	0.1028	0.186	0.0899	0.0349	0.0133
North	UF2 - 20 cm	2.005	1.483	0.7948	0.5168	0.3572	0.4778	0.4407	0	0.33	0.284	0.1542	0.1429
North	UF2 - 50 cm	1.409	0.5233	0.178	0.2588	0.0034	0.0383	0	0	0.0097	0	0	0
North	F1 - 20 cm	0.2555	0.2922	0.2673	0.173	0.2172	0.1858	0.209	0.2059	0.1787	0.1574	0.1657	0.1776
North	F1 - 50 cm	0.5185	0.3755	0.3155	0.1506	0.0472	0.1015	0.0085	0	0	0.0174	0.0102	0
North	F2 - 20 cm	0.1274	0.1462	0.1803	0.1397	0.1679	0.1525	0.1781	0.1771	0.1482	0.1307	0.1323	0.1317
North	F2 - 50 cm	0.2493	0.24	0.0873	0.0567	0.0407	0.0427	0.0095	0.0161	0.0308	0.0046	0.0027	0
North	F3 - 20 cm	0.1662	0.1857	0.159	0.1128	0.1448	0.1333	0.1501	0.1413	0.1274	0.1271	0.1291	0.138
North	F3 - 50 cm	0.1351	0.1099	0.0727	0.0429	0.0235	0.042	0.0181	0.0161	0.0331	0.0191	0.0192	0
Middle	U1 - 20 cm		2.321	1.184	0.2608	0.332	0.3772	0.3542	0.3649	0.3499		0.3429	0.3369
Middle	U1 - 50 cm	1.281	1.159	0.7313	0.4813	0.2757	0.1697	0.0529	0.0188	0.0342	0	0	0
Middle	UF1 - 50 cm		0.1549	0.1042	0.0796	0	0	0	0	0	0	0	0
Middle	UF1 - 70 cm		0.1177	0.1421	0.5409	0	0	0	0	0.3555	0	0	0
Middle	UF2 - 20 cm	0.1112	0.1192	0.081	0.0637	0	0	0	0	0	0	0	0
Middle	UF2 - 50 cm	0.1057	0.1112	0.0824	0.052	0	0	0	0	0	0	0	0
Middle	F1 - 20 cm	0.1215	0.1271	0.0888	0.0849	0	0.0025	0	0	0	0	0	0
Middle	F1 - 50 cm	0.091	0.0783	0.0582	0.0431	0	0	0	0	0	0	0	0
Middle	F2 - 20 cm	0.0662	0.0884	0.0587	0.045	0	0	0	0	0	0	0	0
Middle	F2 - 50 cm	0.1386	0.0958	0.0667	0.0684	0	0			0	0	0	0
Middle	F3 - 20 cm	0.1651	0.0491	0.0305	0.0313	0	0	0	0	0	0	0	0
Middle	F3 - 50 cm	0.1009	0.0536	0.0629	0.0545	0	0	0	0	0	0	0	0
South	U1 - 20 cm				0.5365	0.0618		0.1658					0.1672
South	U1 - 50 cm				2.319					40.99			
South	UF1 - 50 cm			0.2405			0	0.1543	0	22.76	17.11	0.0326	18.76
South	UF1 - 70 cm					0							69.21
South	UF2 - 20 cm	0.1554	0.1992	0.1539	0.0303	0.0852	0.2881	0.0812	0.0606	0.0796	0.0479	0.04	0.0545
South	UF2 - 50 cm	0.5189	0.3117	0.3207	0.0189	0.187	0.1264	0.2356	0	0.058	0	0	0
South	F1 - 20 cm	0.3081	0.2402	0.1503	0.0895	0.0611	0.0854	0.0511	0.0536	0.0513	0.05	0.0248	0.0439
South	F1 - 50 cm	0.0727	0.0635	0.0422	0	0	0	0	0	0	0	0	0
South	F2 - 20 cm	0.0979	0.1361	0.0898	0.0439	0.0319	0.0599	0.045	0.0206	0.0195	0.0228	0	0
South	F2 - 50 cm	0.1066	0.1132	0.1267	0.067	0.0522	0.0629	0.0758	0.0504	0.0437	0.0399	0.0317	0.0228
South	F3 - 20 cm	0.1096	0.1228	0.0852	0.0141	0.0141	0.0067	0	0	0	0	0	0
South	F3 - 50 cm	0.1088	0.0943	0.0907	0.0726	0.0209	0.0381	0.0827	0.0224	0.0273	0.0469	0.0186	0.0123

Table 14: Ammonium concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.291	0.0129	0.0175	0.0105	0.0109			0.00656	
North	U1 - 50 cm	0.21		0.182	0.0436	0	0.00136	0.00707	0	0.0133		0	0.00821
North	UF1 - 50 cm		0.121	0.0161	0.0107	0.000238	0	0.0299	0.0065	0.00696	0	0.0122	0
North	UF1 - 70 cm				0.0282	0	0	0	0	0	0	0	0
North	UF2 - 20 cm	0.636	0.579	0.905	0.869	0.679	0.125	0.729	0.00487	0.314	0.231	0.463	0.497
North	UF2 - 50 cm	0.132	0.0401	0.0488	0.0368	0.000393	0.000502	0.0352	0	0	0	0.0158	0
North	F1 - 20 cm	0.407	0.339	0.303	0.217	0.0124	0.0122	0.182	0.0694	0.00463	0.565	0.336	0.521
North	F1 - 50 cm	0.755	0.592	0.466	0.418	0	0.00145	0	0	0	0	0.233	0.324
North	F2 - 20 cm	0.781	0.731	0.613	0.675	0.711	0.628	0.648	0.69	0.701	0.663	0.663	0.577
North	F2 - 50 cm	0.852	0.735	0.588	0.625	0.723	0.654	0.606	0.656	0.645	0.592	0.612	0.553
North	F3 - 20 cm	0.742	0.735	0.621	0.731	0.731	0.948	0.928	0.953	0.929	1.05	1.03	0.805
North	F3 - 50 cm	0.755	0.937	0.685	0.797	0.691	0	0.818	0.859	0.922	0.875	0.879	0.642
Middle	U1 - 20 cm		0	0.051	0.0936	0.00504	0.00229	0	0	0		0	0
Middle	U1 - 50 cm	0.0611	0.00801	0.0318	0.0927	0	0	0	0.000188	0	0	0	0
Middle	UF1 - 50 cm		0.188	0.0883	0.107	0	0	0	0	0	0	0	0
Middle	UF1 - 70 cm		0.148	0.285	0.0313	0	0.000638	0	0	0	0	0	0
Middle	UF2 - 20 cm	0.52	0.469	0.48	0.644	0	0	0	0	0	0	0	0.335
Middle	UF2 - 50 cm	0.316	0.304	0.305	0.306	0	0	0	0	0	0	0	0
Middle	F1 - 20 cm	0.747	0.716	0.834	0.851	0	0	0	0	0	0	0	0.556
Middle	F1 - 50 cm	0.295	0.274	0.261	0.256	0	0	0	0.00051	0	0	0	0.00834
Middle	F2 - 20 cm	0.385	0.258	0.319	0.288	0	0	0	0	0.377	0.375	0.423	0.414
Middle	F2 - 50 cm	0.878	0.704	0.889	0.958	0	0.732			0.284	0.857	0.695	0.692
Middle	F3 - 20 cm	0.131	0.0794	0.139	0.177	0	0.00239	0	0	0.102	0.335	0.357	0.323
Middle	F3 - 50 cm	1.66	1.31	1.46	1.6	0	0	0	1.25	1.55	1.63	1.35	1.39
South	U1 - 20 cm				0.246	0		0					0
South	U1 - 50 cm				0.0121					0.203			
South	UF1 - 50 cm			0.0251		8.69	0	0	0	0.00479	0.0309	0	0
South	UF1 - 70 cm				1.35	0							0.122
South	UF2 - 20 cm	0.167	0.12	0.2	0.234	0.00944	0.00979	0.00212	0.0064	0	0	0.101	0.285
South	UF2 - 50 cm	1.23	1.09	1.24	1.41	0.00555	0	0.000797	0	0	1.03	0.542	0.893
South	F1 - 20 cm	0.323	0.442	0.619	0.812	0.00742	0	0	0.0032	0	0	0.786	0.934
South	F1 - 50 cm	2.11	2.01	2.26	2.37	0.805	0.641	0	1.96	1.06	2.43	2.28	2.01
South	F2 - 20 cm	0.021	0.0749	0.116	0.273	0.00512	0.00318	4.49E-05	0.000187	0	0.00202	0.548	0.569
South	F2 - 50 cm	0.525	0.673	0.591	0.684	0.0202	0.0022	0	0.00212	0	0.0931	0.771	0.905
South	F3 - 20 cm	0.183	0.164	0.181	0.221	0.00527	0.00251	0	0	0	0	0.117	0.227
South	F3 - 50 cm	0.924	0.833	0.823	1.06	0.00742	0	0	0.0017	0	0	0.835	2.86

Table 15: Dissolved organic carbon concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				43.42	70.09	53.72	42.36	40.97			30.59	
North	U1 - 50 cm	9.497		6.898	6.503	18.88	7.193	10.41	15.3	18.34		32.05	38.3
North	UF1 - 50 cm		3.451	3.308	3.331	23.48	3.668	3.71	5.126	3.661	23.11	23.24	26.38
North	UF1 - 70 cm				1.762	21.54	2.135	1.926	2.273	1.778	23.1	23.72	22.69
North	UF2 - 20 cm	31.57	27.29	26.25	41.29	45.66	34.91	34.71	2.154	30.99	36.77	31.54	34.11
North	UF2 - 50 cm	2.871	2.433	1.683	3.683	21.7	2.202	2.112	2.702	2.282	18.5	19.09	18.58
North	F1 - 20 cm	42.91	37.15	44.57	43.24	56.63	43.22	43.63	48.06	42.95	40.78	42.58	44.9
North	F1 - 50 cm	6.009	4.524	3.125	2.981	19.72	2.06	2.272	2.727	2.373	17.92	17.8	18.38
North	F2 - 20 cm	13.9	26.56	25.89	34.48	46.48	42.02	38.96	41.35	38.19	41.79	38.12	41.13
North	F2 - 50 cm	3.73	2.958	2.323	3.641	15.24	4.331	2.212	4.2	3.982	12.36	12.73	12.63
North	F3 - 20 cm	12.81	28.86	28.55	31.29	43.54	34.51	33.86	37.02	34.89	39.58	39.27	40.63
North	F3 - 50 cm	2.958	3.564	21.43	2.573	17.29	4.061	3.876	4.042	4.048	13.5	12.9	13.21
Middle	U1 - 20 cm		22.35	20.34	20.25	35.1	19.96	19.18	20.46	20.27		35.28	33.74
Middle	U1 - 50 cm	12.93	9.142	14.04	13.28	42.46	13.13	14.15	14.48	12.74	40.45	40.11	43.05
Middle	UF1 - 50 cm		3.958	3.593	3.778	46.77	2.895	2.278	2.77	1.958	40.7	39.09	41.52
Middle	UF1 - 70 cm		2.986	2.851	1.884	40.87	2.105	3.747	1.486	1.241	39.19	38.3	38.65
Middle	UF2 - 20 cm	10.59	10.6	6.719	11.18	36.74	12.69	13.98	14.76	17.89	38.06	37.46	38.79
Middle	UF2 - 50 cm	2.294	1.047	1.851	1.915	40.83	2.161	2.361	2.234	2.259	41.84	36.54	42.79
Middle	F1 - 20 cm	8.273	6.334	6.998	8.847	33.34	8.122	10.04	9.358	10.26	36.87	35.5	37.04
Middle	F1 - 50 cm	1.77	2.663	1.769	4.544	1.869	1.87	2.034	1.985	1.796	37.38	36	36.65
Middle	F2 - 20 cm	13.3	14.56	15.82	0.09086	17.07	17.97	19.12	18.11	18.04	36.02	35.73	37.01
Middle	F2 - 50 cm	8.82	8.506	8.424	9.076	8.584	7.851			8.482	35.08	36.11	35.04
Middle	F3 - 20 cm	18.03	17.84	19.25	19.96	20.15	18.49	19.52	19.08	30.94	30.44	35.07	33.75
Middle	F3 - 50 cm	8.07	8.576	8.65	8.67	8.775	8.402	9.373	8.635	34.99	33.89	35.4	34.72
South	U1 - 20 cm				41.19	9.448		9.67					37.47
South	U1 - 50 cm				47.58					46.66			
South	UF1 - 50 cm			4.483		9.817	2.026	2.821	2.752	45.12	44.48	44.47	47.74
South	UF1 - 70 cm				47.99	2.841							40.71
South	UF2 - 20 cm	34.96	34.88	39.47	30.31	40.65	39.12	34.58	34.67	41.8	40.02	37.62	39.01
South	UF2 - 50 cm	14.9	38.69	11.32	22.23	10.67	16.57	13.29	15.62	35.21	34.4	34.51	35.4
South	F1 - 20 cm	34.52	3.232	31.64	44.78	32.82	34.82	28.98	30.98	43.01	42.7	40.76	41.57
South	F1 - 50 cm	6.219	40.5	5.382	36.65	6.862	8.265	6.053	5.885	31.37	30.06	30.16	30.08
South	F2 - 20 cm	31.6	28.01	40.42	52.06	38.13	39.74	33.09	26.58	41.36	38	35.36	34.42
South	F2 - 50 cm	26.99	25.89	28.55	42.43	32.12	33.85	35.13	25.64	38.79	36.91	35.12	33.06
South	F3 - 20 cm	29.47	30.51	32.95	45.78	32.96	32.22	31.65	22.87	38.11	36.39	33.21	33.77
South	F3 - 50 cm	14.14	14.87	14	30.26	15.86	14.91	16.36	13.57	26.12	25.28	25.39	23.71

Table 16: Iron concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				1.379	1.885	1.596	1.111	1.119			0.7592	
North	U1 - 50 cm	10		2.812	2.131	1.651	1.164	1.586	1.154	1.556		1.842	2.47
North	UF1 - 50 cm		1.116	0.1678	0.1506	0.1045	0.073	0.0493	0.1267	0.0344	0.0037	0.0426	0.1268
North	UF1 - 70 cm				0.7757	0.1333	0.0897	0.1032	0.0723	0.1466	0.0706	0.0566	0.0432
North	UF2 - 20 cm	3.579	3.302	3.991	3.927	3.389	3.063	2.871	0	1.737	0.9175	0.799	0.7995
North	UF2 - 50 cm	0.5736	0.5102	0.4397	0.372	0.1563	0.1636	0.3916	0.1425	0.3199	0.1617	0.1713	0.1461
North	F1 - 20 cm	1.383	1.646	1.626	1.481	2.078	1.842	1.766	1.678	1.567	1.319	1.3	1.387
North	F1 - 50 cm	0.8732	0.3605	0.246	0.1918	0.1771	0.1427	0.2666	0.1724	0.1846	0.1402	0.2161	0.2411
North	F2 - 20 cm	1.07	1.124	1.273	1.456	1.814	1.87	1.649	1.665	1.573	1.445	1.141	1.355
North	F2 - 50 cm	0.1955	0.5033	0.4311	0.5511	0.7323	0.5705	0.3007	0.377	0.4229	0.2104	0.3246	0.3505
North	F3 - 20 cm	1.096	1.172	1.171	1.189	1.142	1.135	1.154	1.353	1.134	1.228	1.317	1.407
North	F3 - 50 cm	0.3917	0.79	0.2943	0.3251	0.635	0.7901	0.3945	0.6333	0.878	0.5972	0.7094	0.2266
Middle	U1 - 20 cm		2.984	1.294	0.3632	0.6356	0.566	0.3489	0.3006	0.3185		0.2608	0.2526
Middle	U1 - 50 cm	1.055	0.9512	0.6148	0.8621	0.6884	0.2838	0.5741	0.3209	0.1262	0.044	0.1581	0.1118
Middle	UF1 - 50 cm		0.04	0.0086	0.0521	0.0291	0.1358	0.0657	0.0696	0.127	0.1632	0.067	0.0807
Middle	UF1 - 70 cm		0.022	0.0146	0.2726	0	0.0097	0	0	0.1693	0	0.0022	0
Middle	UF2 - 20 cm	0.4741	0.3385	0.3522	0.5863	0.197	0.5687	0.7576	0.7638	0.8694	0.6188	0.242	0.482
Middle	UF2 - 50 cm	0	0	0	0.0365	0	0	0	0	0	0	0	0.0022
Middle	F1 - 20 cm	0.2105	0.197	0.3992	0.6087	0.2038	0.2088	0.5528	0.6267	0.6749	0.5246	0.2686	0.5037
Middle	F1 - 50 cm	0.0004	0	0	0.034	0	0	0	0	0	0	0	0.0005
Middle	F2 - 20 cm	0.241	0.2113	0.2757	0.3762	0.1931	0.5115	0.2468	0.6218	0.5527	0.296	0.3199	0.5696
Middle	F2 - 50 cm	0.3492	0.2187	0.1569	0.3704	0.3127	0.0874			0.4913	0.0576	0.0333	0.0552
Middle	F3 - 20 cm	0.3005	0.2899	0.3855	0.6931	0.6574	0.3512	0.4092	0.5161	0.63	0.6074	0.6861	0.374
Middle	F3 - 50 cm	0.3526	0.177	0.0799	0.3192	0.3931	0.1285	0.2231	0.7338	0.9075	0.6636	0.2332	0.4113
South	U1 - 20 cm				0.5853	0.1205		0.188					0.266
South	U1 - 50 cm				1.479					23.28			
South	UF1 - 50 cm			0.1074			0.0138	0.1267	0.0212	14.73	11.85	0.0658	13
South	UF1 - 70 cm					0.0041							40.32
South	UF2 - 20 cm	3.387	3.92	4.166	1.467	6.526	5.57	4.256	5.788	5.031	3.41	3.456	4.043
South	UF2 - 50 cm	7.228	7.101	6.027	0.3817	7.57	8.435	6.556	10.31	7.651	6.011	4.645	5.058
South	F1 - 20 cm	3.197	4.105	3.438	4.842	5.593	5.281	3.239	4.795	5.084	4.522	2.898	4.575
South	F1 - 50 cm	2.646	2.997	0.7021	3.747	5.207	5.772	0.2394	1.942	2.852	0.6796	1.032	0.3485
South	F2 - 20 cm	2.505	3.951	5.632	5.961	8.432	6.937	5.739	5.209	5.327	5.319	4.426	4.995
South	F2 - 50 cm	3.858	3.73	3.565	5.027	5.398	5.922	5.322	4.972	4.368	4.651	4.676	4.946
South	F3 - 20 cm	3.451	4.378	3.799	4.507	4.935	4.658	4.174	3.408	4.569	5.144	2.023	3.194
South	F3 - 50 cm	2.196	1.869	1.639	3.669	4.508	4.425	3.835	3.534	4.8	4.242	3.405	1.566

Table 17: Magnesium concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				3.244	3.866	3.823	2.875	2.955			1.604	
North	U1 - 50 cm	4.926		4.079	4.418	4.886	4.973	4.866	5.264	5.554		6.563	6.18
North	UF1 - 50 cm		6.362	6.172	7.098	6.985	6.79	7.046	7.464	7.035	7.031	7.526	7.353
North	UF1 - 70 cm				6.421	6.569	6.505	6.541	6.598	6.534	6.527	6.922	6.95
North	UF2 - 20 cm	3.84	3.842	3.826	3.499	3.92	3.8	3.827	-0.0013	3.896	3.885	3.335	3.662
North	UF2 - 50 cm	7.044	7.428	7.325	7.409	6.766	6.681	6.8	6.812	6.522	6.418	6.771	6.821
North	F1 - 20 cm	2.355	2.482	2.582	2.119	2.687	2.552	2.652	2.605	2.459	2.32	2.5	2.612
North	F1 - 50 cm	6.892	5.976	6.664	5.605	5.974	5.684	6.095	6.23	6.224	6.155	6.256	6.088
North	F2 - 20 cm	2.546	2.567	2.772	2.506	2.733	2.845	2.893	2.95	2.876	2.874	3.01	3.063
North	F2 - 50 cm	3.324	3.405	3.159	2.903	3.041	3.037	3.12	3.216	3.104	3.161	3.274	3.349
North	F3 - 20 cm	2.751	2.566	2.459	2.241	2.631	2.431	2.738	2.724	2.648	2.64	2.693	2.925
North	F3 - 50 cm	2.955	3.086	2.704	2.353	2.834	2.686	2.62	2.982	2.934	3.008	2.87	2.823
Middle	U1 - 20 cm		7.068	6.031	3.563	5.25	5.006	5.905	6.003	5.821		6.626	6.656
Middle	U1 - 50 cm	9.184	9.87	9.615	10.98	11.06	11.05	11.58	11.82	11.57	11.81	12.68	13.4
Middle	UF1 - 50 cm		13.97	14.06	16.15	14.08	14.26	12.68	12.46	12	12.24	12.08	12.35
Middle	UF1 - 70 cm		13.81	13.12	11.92	12.78	12.8	11.82	11.73	11.82	11.7	11.44	11.59
Middle	UF2 - 20 cm	7.641	7.512	7.74	7.299	9.149	8.297	8.28	7.693	6.971	6.465	7.767	8.703
Middle	UF2 - 50 cm	11.85	12.45	11.5	10.98	11.7	12.09	11.53	11.56	11.64	11.58	11.53	11.58
Middle	F1 - 20 cm	7.228	7.958	7.663	7.991	7.805	8.051	7.922	8.151	7.962	7.907	7.791	7.698
Middle	F1 - 50 cm	10.73	10.78	9.588	8.769	10.58	10.5	10.31	10.12	10.28	10.3	10.41	10.48
Middle	F2 - 20 cm	4.976	5.024	4.848	4.582	5.283	5.294	5.319	5.488	5.539	5.475	5.792	6.069
Middle	F2 - 50 cm	7.665	7.658	6.689	6.648	7.457	7.772			7.836	7.359	7.538	7.541
Middle	F3 - 20 cm	3.812	3.965	3.938	3.886	4.577	4.504	4.324	4.393	4.307	4.355	4.789	4.965
Middle	F3 - 50 cm	7.2	7.267	6.482	6.324	6.734	6.839	6.827	7.194	7.399	7.125	7.332	7.588
South	U1 - 20 cm				8.033	13.74		10.82					9.275
South	U1 - 50 cm				12.38					17.73			
South	UF1 - 50 cm			8.746			9.538	11.54	11.47	15.41	13.73	11.77	15.43
South	UF1 - 70 cm					11.93							19.62
South	UF2 - 20 cm	2.837	2.96	3.026	2.198	4.52	4.721	3.807	4.091	4.068	4.104	4.25	4.173
South	UF2 - 50 cm	5.966	6.395	5.995	6.084	6.187	6.153	6.154	6.41	6.226	6.076	6.436	6.502
South	F1 - 20 cm	2.983	3.22	3.236	3.629	3.979	4.312	4.141	4.094	4.169	4.244	4.41	4.691
South	F1 - 50 cm	7.98	8.257	7.876	7.736	8.219	7.891	7.875	8.259	8.289	8.564	7.765	8.062
South	F2 - 20 cm	2.993	3.221	3.742	3.966	4.874	4.652	4.067	4.349	4.404	4.664	4.31	4.749
South	F2 - 50 cm	3.36	3.128	3.174	3.681	4.235	4.457	4.487	4.432	4.461	4.393	4.266	4.728
South	F3 - 20 cm	3.272	4.196	4.162	5.063	5.483	5.382	5.77	5.703	5.779	5.96	6.329	6.338
South	F3 - 50 cm	3.861	3.473	2.721	3.423	3.614	3.774	3.24	3.884	3.84	4.013	3.854	3.824

Table 18: Manganese concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.0073	0.0037	0.0019	0.0032	0.0011			0.0006	
North	U1 - 50 cm	0.0629		0.0227	0.0164	0.0073	0.0044	0.0042	0.0047	0.0063		0.0079	0.0092
North	UF1 - 50 cm		0.0104	0.8107	1.068	1.118	0.6985	0.9398	1.132	1.013	0.9191	1.063	1.202
North	UF1 - 70 cm				0.8243	0.6471	0.212	0.4441	0.7622	1.036	0.9799	1.079	1.21
North	UF2 - 20 cm	0.0025	0.0012	0.0015	0.0073	0.0036	0.0029	0.0854	0.0003	0.0089	0.0076	0.0021	0.0016
North	UF2 - 50 cm	0.0018	0.164	0.1639	0.1348	0	0.0018	0.0026	0.1551	0.0866	0.1794	0.0497	0.077
North	F1 - 20 cm	0.0009	0.0014	0.009	0.0133	0.0356	0.0063	0.0516	0.0385	0.0309	0.0308	0.0249	0.0284
North	F1 - 50 cm	0.0015	0.0013	0.0009	0.0057	0	0	0.0001	0.0007	0.0006	0.0006	0	0.0007
North	F2 - 20 cm	0.0029	0.0195	0.0389	0.0591	0.0599	0.0497	0.0634	0.0637	0.0615	0.0627	0.0066	0.0379
North	F2 - 50 cm	0.0008	0	0.004	0.0074	0.0074	0.0004	0	0.0025	0.0022	0.0015	0.0003	0.0015
North	F3 - 20 cm	0.0012	0.0032	0.0064	0.0216	0.0326	0.0028	0.0215	0.0261	0.0038	0.0375	0.0284	0.0203
North	F3 - 50 cm	0	0.0006	0	0.0057	0	0.0004	0.0006	-0.0004	0.0002	0.0012	0	0.0012
Middle	U1 - 20 cm		0.0106	0.0038	0.0055	0.0008	0.001	0.0007	0.0007	0.0011		0	0.0008
Middle	U1 - 50 cm	0.0054	0.0042	0.0007	0.0331	0.0021	0.0004	0.0199	0.0049	0.0007	0.0003	0	0
Middle	UF1 - 50 cm		0	0	0.0041	0.0002	0	0	0.0001	0.0001	0.0001	0	0.0001
Middle	UF1 - 70 cm		0.0014	0	0.0084	0.0056	0	0.0003	0.0041	0.0011	0.0004	0.0005	0
Middle	UF2 - 20 cm	0.0005	0	0	0.0041	0	0.0006	0.0001	0.0004	0.0002	0.0011	0	0.0001
Middle	UF2 - 50 cm	0.0002	0	0	0.0053	0	0	0.0004	0.0003	0.0003	0.0006	0	0
Middle	F1 - 20 cm	0.0003	0	0	0.0047	0	0	0	0.0013	0.0013	0.0016	0	0
Middle	F1 - 50 cm	0	0.0003	0	0.0053	0	0	0.0006	0.0003	0.0002	0.0008	0	0.0002
Middle	F2 - 20 cm	0.0003	0	0	0.0084	0	0.0001	0.0005	0.0014	0.0011	0.0006	0	0.0002
Middle	F2 - 50 cm	0	0	0	0.008	0	0			0	0.0007	0.0002	0
Middle	F3 - 20 cm	0.0023	0	0.0001	0.0074	0	0	0.001	0.0007	0.0005	0.0007	0	0
Middle	F3 - 50 cm	0.0008	0.0004	0	0.0078	0	0	0.0001	0.0005	0.0003	0.0004	0	0.0003
South	U1 - 20 cm				0.001	0.0003		0.0011					0.0004
South	U1 - 50 cm				0.0088					0.3499			
South	UF1 - 50 cm			0.0001			0.0006	0.0002	0.0001	0.126	0.0647	0	0.0802
South	UF1 - 70 cm					0							0.2467
South	UF2 - 20 cm	0.0027	0.0036	0.0028	0.0032	0.001	0.0023	0.0009	0.0024	0.0018	0.003	0.001	0.002
South	UF2 - 50 cm	0.0015	0.0024	0	0.0003	0.0003	0.0053	0.0008	0.1108	0.0012	0.0024	0.0011	0.001
South	F1 - 20 cm	0.0014	0.0025	0.0022	0	0.0011	0.0024	0.0023	0.0024	0.0021	0.0014	0.0027	0.0054
South	F1 - 50 cm	0.0004	0.0008	0.0003	0.002	0.0003	0.0031	0	0.0003	0.0006	0.0007	0.0004	0.0015
South	F2 - 20 cm	0.0026	0.0022	0.01	0.0037	0.0052	0.0097	0.0035	0.0071	0.0034	0.0037	0.0012	0.0033
South	F2 - 50 cm	0.0034	0.0013	0.0076	0.0001	0.0048	0.0076	0.0038	0.0076	0.0077	0.0077	0.0064	0.0019
South	F3 - 20 cm	0.0002	0.0015	0.0053	0.0002	0.0003	0.0018	0.0024	0.0011	0.0018	0.0031	0	0.0006
South	F3 - 50 cm	0.0028	0.0018	0.0057	0	0	0.0003	0.0002	0.0009	0.0008	0.0015	0.0003	0.0005

Table 19: Nitrate-nitrite concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.0275	0.27	0.203	0.437	0.203			0.603	
North	U1 - 50 cm	0.00898		0	0	0.0251	0.0293	0.0127	0.0293	0.00372		0	0
North	UF1 - 50 cm		0.0575	0	0	0.0144	0.023	0.0105	0.00824	0.0125	0.0064	0.00317	0
North	UF1 - 70 cm				0	0.0299	1.05	0.95	0.812	0.386	0.249	0.147	0.104
North	UF2 - 20 cm	0	0	0	0	0.104	0.726	0.0196	0.566	0.169	0.179	0.152	0.00616
North	UF2 - 50 cm	0	0	0	0	0.0627	0.0395	0.0148	0.0478	0.0661	0.00798	0.00269	0
North	F1 - 20 cm	0.00479	0	0	0	0.355	0.426	0.172	0.257	0.37	0.0647	0.0498	0.00217
North	F1 - 50 cm	0	0.00349	0	0	0.44	0.466	0.486	0.41	0.404	0.451	0.163	0.0088
North	F2 - 20 cm	0	0	0	0	0.0253	0.0435	0.0214	0.00329	0.0178	0.00148	0.00221	0
North	F2 - 50 cm	0	0	0	0	0.0156	0.0162	0.00202	0.00126	0.0343	0.0022	0.00035	0
North	F3 - 20 cm	0	0	0	0	0.0312	0.0537	0.00891	0.00452	0.103	0.0183	0.00118	0.000496
North	F3 - 50 cm	0	0	0	0	0.206	0.902	0.0532	0.0124	0.0187	0.00736	0.00116	0.00365
Middle	U1 - 20 cm		0	0	0	0.131	0.122	0.413	0.0972	0.189		0.138	0.098
Middle	U1 - 50 cm	0	0	0	0	0.264	0.295	0.246	0.158	0.111	0.125	0.0088	0.0381
Middle	UF1 - 50 cm		0.0565	0	0	0.101	0.069	0.0873	0.084	0.0511	0.0625	0.0815	0.0214
Middle	UF1 - 70 cm		0.0221	0	0	0.0745	0.0447	0.0598	0.0369	0.0432	0.0298	0.0349	0.0388
Middle	UF2 - 20 cm	0.0996	0	0	0	0.543	0.654	0.706	0.654	0.674	0.589	0.535	0.192
Middle	UF2 - 50 cm	0.0673	0	0	0	0.299	0.265	0.289	0.281	0.312	0.27	0.278	0.214
Middle	F1 - 20 cm	0.0477	0	0	0	0.803	0.768	0.771	0.767	0.79	0.759	0.593	0.0483
Middle	F1 - 50 cm	0	0	0	0	0.27	0.255	0.279	0.249	0.283	0.281	0.21	0.191
Middle	F2 - 20 cm	0.0089	0	0	0	0.331	0.397	0.328	0.422	0.149	0.0458	0.0192	0
Middle	F2 - 50 cm	0	0	0	0	1.45	0.23			0.978	0.0298	0.0048	0.000779
Middle	F3 - 20 cm	0	0	0	0	0.285	0.286	0.315	0.278	0.297	0.17	0.0176	0.00838
Middle	F3 - 50 cm	0	0	0	0	2.49	1.84	1.77	0.604	0.184	0.0214	0.0051	0.000805
South	U1 - 20 cm				0.00802	0.955		0.574					0.769
South	U1 - 50 cm				0					0.875			
South	UF1 - 50 cm			0		1.76	0.0753	0	0	0.0458	0.0683	0.000474	0.0248
South	UF1 - 70 cm				0.0218	0.0208							0.352
South	UF2 - 20 cm	0	0	0	0	0.404	0.418	0.302	0.315	0.342	0.236	0.289	0.0508
South	UF2 - 50 cm	0.0046	0	0	0	1.45	1.11	1.06	1.18	1.16	0.1	0.403	0.078
South	F1 - 20 cm	0.0244	0	0	0	0.878	0.747	0.689	0.731	0.844	0.853	0.0878	0.0338
South	F1 - 50 cm	0	0	0	0	2.01	1.65	1.98	0.517	1.47	0.0102	0.0339	0.00759
South	F2 - 20 cm	0	0	0	0	0.51	0.462	0.494	0.519	0.562	0.594	0.0707	0.0243
South	F2 - 50 cm	0	0	0	0.0127	0.789	0.735	0.652	0.728	0.738	0.725	0.175	0.0703
South	F3 - 20 cm	0	0	0	0	0.37	0.324	0.328	0.26	0.374	0.364	0.16	0.0188
South	F3 - 50 cm	0	0	0	0	1.21	1	1	0.954	1.09	1.05	0.132	0

Table 20: Ortho-phosphate concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.0383	0.0258	0.0178	0.0454	0.0115			0.0674	
North	U1 - 50 cm	0.0102		0.0101	0.01	0.00769	0.00719	0.00732	0.00738	0.00863		0.00926	0.0091
North	UF1 - 50 cm		0.0162	0.00719	0.00721	0.00709	0.00755	0.00781	0.00674	0.00639	0.00726	0.00766	0.00777
North	UF1 - 70 cm				0.00807	0.00856	0.0716	0.0542	0.0329	0.0249	0.0202	0.0185	0.0136
North	UF2 - 20 cm	0.0138	0.0142	0.019	0.0216	0.0144	0.012	0.0119	0.0114	0.0084	0.00963	0.0125	0.00948
North	UF2 - 50 cm	0.0108	0.0099	0.0102	0.0171	0.0165	0.0125	0.013	0.0123	0.0149	0.012	0.0145	0.0145
North	F1 - 20 cm	0.00145	0.00188	0.00217	0.00655	0.018	0.0176	0.0192	0.0177	0.0213	0.043	0.0184	0.033
North	F1 - 50 cm	0.0445	0.0261	0.024	0.0183	0.0203	0.0182	0.0207	0.0207	0.0182	0.0218	0.0196	0.0188
North	F2 - 20 cm	0.0273	0.0266	0.0296	0.0329	0.0305	0.0246	0.0316	0.0343	0.0384	0.0369	0.0382	0.0501
North	F2 - 50 cm	0.0368	0.0354	0.0247	0.0311	0.0323	0.0245	0.0233	0.0253	0.0262	0.0197	0.0246	0.0248
North	F3 - 20 cm	0.0351	0.0236	0.0311	0.046	0.0496	0.0558	0.0639	0.07	0.0651	0.0639	0.0661	0.0653
North	F3 - 50 cm	0.0117	0.023	0.0118	0.0156	0.0244	0.0187	0.014	0.0243	0.0234	0.0194	0.0171	0.014
Middle	U1 - 20 cm		0.00938	0.00918	0.02	0.0154	0.0137	0.0424	0.0121	0.0157		0.0176	0.0127
Middle	U1 - 50 cm	0.00665	0.0082	0.00692	0.014	0.0164	0.0195	0.0121	0.0103	0.015	0.013	0.00694	0.00761
Middle	UF1 - 50 cm		0.0152	0.0117	0.0649	0.0153	0.0176	0.014	0.0121	0.0141	0.0146	0.0117	0.0103
Middle	UF1 - 70 cm		0.021	0.0229	0.0217	0.0224	0.0226	0.0259	0.0269	0.0277	0.0258	0.029	0.0319
Middle	UF2 - 20 cm	0.0339	0.0322	0.035	0.0542	0.031	0.0523	0.075	0.0785	0.0911	0.0905	0.0565	0.071
Middle	UF2 - 50 cm	0.0443	0.0385	0.0365	0.0417	0.0381	0.0312	0.0389	0.0354	0.0377	0.0363	0.0355	0.0378
Middle	F1 - 20 cm	0.0406	0.0408	0.0619	0.071	0.0534	0.0502	0.0618	0.0673	0.0696	0.0622	0.0566	0.0702
Middle	F1 - 50 cm	0.0387	0.0373	0.0317	0.0381	0.035	0.0279	0.0317	0.0245	0.0334	0.033	0.0277	0.028
Middle	F2 - 20 cm	0.0285	0.0326	0.0341	0.0565	0.0448	0.0569	0.0502	0.0657	0.0667	0.0665	0.076	0.0855
Middle	F2 - 50 cm	0.0555	0.0507	0.0491	0.0604	0.061	0.057			0.0664	0.0479	0.0435	0.0533
Middle	F3 - 20 cm	0.0339	0.0206	0.0328	0.0395	0.0516	0.0391	0.0451	0.0422	0.0516	0.0658	0.0602	0.0697
Middle	F3 - 50 cm	0.121	0.101	0.0774	0.0925	0.0905	0.0738	0.0735	0.111	0.114	0.103	0.0681	0.0984
South	U1 - 20 cm				0.0336	0.0393		0.0379					0.0632
South	U1 - 50 cm				0.491					0.0432			
South	UF1 - 50 cm			0.00576			0.0104	0.0127	0.0141	0.0288	0.0328	0.0191	0.0294
South	UF1 - 70 cm				0.078	0.0238							0.347
South	UF2 - 20 cm	0.0116	0.0193	0.0268	0.0168	0.051	0.0488	0.0375	0.057	0.0498	0.0432	0.0373	0.0606
South	UF2 - 50 cm	0.0969	0.104	0.137	0.0452	0.155	0.165	0.112	0.177	0.144	0.128	0.0879	0.0584
South	F1 - 20 cm	0.0155	0.0199	0.0304	0.0624	0.0795	0.0917	0.047	0.0931	0.105	0.103	0.0571	0.0846
South	F1 - 50 cm	0.0242	0.0403	0.0449	0.0625	0.0948	0.109	0.0377	0.0576	0.083	0.038	0.024	0.0153
South	F2 - 20 cm	0.017	0.0523	0.0729	0.0806	0.0837	0.0921	0.0977	0.0912	0.122	0.137	0.095	0.0983
South	F2 - 50 cm	0.047	0.0368	0.035	0.0685	0.0612	0.0824	0.0733	0.0744	0.0667	0.0757	0.0797	0.101
South	F3 - 20 cm	0.0165	0.0238	0.0318	0.0567	0.0676	0.0673	0.0586	0.05	0.0731	0.0845	0.0399	0.0495
South	F3 - 50 cm	0.0197	0.0173	0.00959	0.0325	0.0502	0.0436	0.0326	0.0401	0.0527	0.0438	0.0356	0.0226

Table 21: Potassium concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.6804	0.3747	0.3366	0.5911	0.5483			0.6412	
North	U1 - 50 cm	1.061		0.4151	0.494	0.3844	0.3564	0.3854	0.407	0.4215		0.4807	0.3987
North	UF1 - 50 cm		0.6915	0.3574	0.5309	0.4137	0.3892	0.4599	0.4575	0.4547	0.4631	0.5017	0.4485
North	UF1 - 70 cm				0.7874	0.5545	0.7163	0.7286	0.6748	0.6129	0.5968	0.6293	0.6189
North	UF2 - 20 cm	0.4522	0.3838	0.3809	0.4267	0.2549	0.2518	0.2566	0	0.246	0.2191	0.2193	0.1941
North	UF2 - 50 cm	0.54	0.4268	0.3274	0.3039	0.319	0.2907	0.358	0.3494	0.3643	0.3609	0.368	0.3773
North	F1 - 20 cm	0.575	0.7068	0.5574	0.2436	0.3441	0.3244	0.3651	0.3465	0.3593	0.4033	0.3459	0.3795
North	F1 - 50 cm	0.9334	0.5773	0.7583	0.5155	0.512	0.4904	0.5959	0.5853	0.5676	0.6112	0.5845	0.5347
North	F2 - 20 cm	0.4747	0.447	0.5973	0.509	0.3817	0.3924	0.4285	0.4342	0.4234	0.4605	0.5217	0.5144
North	F2 - 50 cm	0.5128	0.5155	0.3757	0.3258	0.4084	0.3559	0.4003	0.4092	0.4947	0.4124	0.4428	0.4586
North	F3 - 20 cm	0.4846	0.3782	0.3118	0.3552	0.4191	0.3369	0.4789	0.4818	0.4649	0.4564	0.4493	0.5281
North	F3 - 50 cm	0.498	0.4205	0.4106	0.3664	0.3668	0.3767	0.4204	0.404	0.418	0.4542	0.3873	0.3932
Middle	U1 - 20 cm		1.249	0.9287	0.7684	0.6692	0.6213	0.6525	0.5943	0.616		0.6231	0.6912
Middle	U1 - 50 cm	0.5193	0.4819	0.3183	0.4358	0.2979	0.2835	0.3019	0.2827	0.3028	0.294	0.2868	0.3547
Middle	UF1 - 50 cm		0.9866	0.8751	1.241	0.7726	0.7565	0.8965	0.7918	0.7952	0.8173	0.8166	0.8474
Middle	UF1 - 70 cm		1.661	1.322	1.16	1.118	1.114	1.31	1.279	1.418	1.352	1.293	1.311
Middle	UF2 - 20 cm	1.615	1.407	1.249	1.093	1.166	1.063	1.253	1.129	1.055	1.025	1.099	1.255
Middle	UF2 - 50 cm	1.599	1.825	1.547	1.286	1.359	1.373	1.593	1.538	1.547	1.58	1.539	1.499
Middle	F1 - 20 cm	1.055	1.437	1.003	1.239	0.9793	0.9797	1.132	1.087	1.184	1.134	1.133	1.601
Middle	F1 - 50 cm	1.544	1.624	1.047	0.8788	1.244	1.162	1.435	1.293	1.335	1.381	1.384	1.343
Middle	F2 - 20 cm	1.801	1.724	0.864	0.7649	0.7863	0.7659	0.8611	0.9013	0.9195	0.9109	0.9046	0.9282
Middle	F2 - 50 cm	1.26	1.097	0.7458	0.8658	0.8865	0.9046			1.051	1.027	1.099	1.038
Middle	F3 - 20 cm	0.8319	0.744	0.409	0.4303	0.4525	0.4609	0.5393	0.3819	0.5157	0.5197	0.666	0.6856
Middle	F3 - 50 cm	1.149	1.182	0.9258	0.8587	0.895	0.8994	1.124	1.062	1.142	1.078	1.159	1.149
South	U1 - 20 cm				1.576	1.05		1.074					1.03
South	U1 - 50 cm				1.645					11.48			
South	UF1 - 50 cm			1.318			1.277	1.382	1.26	6.76	4.582	1.233	5.49
South	UF1 - 70 cm					1.122							17.23
South	UF2 - 20 cm	0.6092	0.5809	0.3133	0.1837	0.4459	0.5717	0.4538	0.5153	0.5125	0.4534	0.5241	0.4604
South	UF2 - 50 cm	1.169	1.395	1.075	1.031	1.01	1.106	1.173	1.065	1.104	1.095	1.159	1.146
South	F1 - 20 cm	0.5295	0.6446	0.5159	0.627	0.6151	0.7754	0.729	0.6924	0.7094	0.7074	0.7309	0.8083
South	F1 - 50 cm	1.266	1.424	1.093	0.9629	0.9895	1.103	1.125	1.078	1.095	1.206	1.026	1.116
South	F2 - 20 cm	0.254	0.4402	0.2866	0.2595	0.5653	0.6926	0.6878	0.663	0.6439	0.704	0.6642	0.8166
South	F2 - 50 cm	1.177	0.89	0.9261	0.6403	0.6018	0.6794	0.7219	0.6964	0.7511	0.7414	0.6919	0.7875
South	F3 - 20 cm	0.7352	0.8222	0.7553	0.5502	0.4553	0.4838	0.5694	0.5154	0.5335	0.5731	0.578	0.555
South	F3 - 50 cm	0.7372	0.6909	1.006	0.5911	0.5706	0.6792	0.6815	0.69	0.6432	0.7158	0.6707	0.651

Table 22: Sodium concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				5.807	6.129	6.133	5.045	4.816			3.762	
North	U1 - 50 cm	5.377		3.44	3.896	3.544	3.586	3.509	3.562	3.514		4.487	3.482
North	UF1 - 50 cm		8.81	3.142	5.509	3.222	3.171	3.437	3.578	3.351	3.411	3.9	3.5
North	UF1 - 70 cm				4.016	3.489	3.536	3.707	3.638	3.571	3.598	4.018	4.03
North	UF2 - 20 cm	3.361	3.398	3.121	2.776	2.772	2.669	2.769	-0.0063	2.693	2.801	2.43	2.568
North	UF2 - 50 cm	3.768	4.094	3.82	4.483	2.669	2.717	2.871	2.939	2.775	2.812	3.237	3.284
North	F1 - 20 cm	2.045	3.107	1.919	1.563	1.558	1.542	1.672	1.632	1.641	1.692	1.813	1.897
North	F1 - 50 cm	4.478	3.145	4.09	2.811	2.561	2.569	2.879	2.878	2.769	2.918	2.91	2.725
North	F2 - 20 cm	2.17	2.323	2.405	1.922	1.71	1.864	1.97	1.98	1.853	2.042	2.197	2.226
North	F2 - 50 cm	3.044	3.783	2.894	2.445	2.629	2.533	2.632	2.727	2.745	2.704	2.988	3.15
North	F3 - 20 cm	2.376	2.328	1.99	1.869	1.967	1.925	2.1	2.035	2.042	2.118	2.032	2.379
North	F3 - 50 cm	3.475	3.495	2.882	2.832	2.947	2.922	3.182	2.991	2.979	3.119	2.983	3.094
Middle	U1 - 20 cm		4.687	3.809	2.55	3.251	3.217	3.814	3.724	3.668		4.844	5.179
Middle	U1 - 50 cm	4.676	4.978	4.154	6.664	4.121	4.153	4.422	4.37	4.361	4.514	4.866	5.479
Middle	UF1 - 50 cm		14.11	8.66	8.487	5.25	4.887	4.718	4.264	4.253	4.38	4.305	4.661
Middle	UF1 - 70 cm		6.54	5.332	3.587	4.019	4.014	4.016	3.864	4.135	4.079	3.938	4.18
Middle	UF2 - 20 cm	3.6	3.56	2.787	2.341	3.005	2.698	2.881	2.603	2.486	2.417	2.731	3.254
Middle	UF2 - 50 cm	4.367	4.926	4.011	3.32	3.444	3.58	3.706	3.598	3.682	3.706	3.736	3.823
Middle	F1 - 20 cm	3.178	4.576	2.78	3.571	2.796	2.797	2.961	2.862	3.082	2.911	3.134	4.314
Middle	F1 - 50 cm	4.106	4.567	2.705	2.273	3.242	3.091	3.402	3.14	3.265	3.374	3.486	3.575
Middle	F2 - 20 cm	3.447	3.519	2.074	1.87	2.19	2.111	2.2	2.26	2.357	2.322	2.49	2.58
Middle	F2 - 50 cm	4.457	3.695	2.414	2.691	2.943	2.971			3.15	3.09	3.439	3.335
Middle	F3 - 20 cm	2.28	2.727	1.705	2.179	1.914	1.869	1.997	1.952	2.133	2.11	2.422	2.422
Middle	F3 - 50 cm	3.528	3.826	2.788	2.569	2.727	2.731	3.12	2.959	3.268	3.022	3.403	3.497
South	U1 - 20 cm				3.979	4.531		4.36					4.841
South	U1 - 50 cm				6.337					10.15			
South	UF1 - 50 cm			9.868			5.005	4.723	4.294	6.764	5.31	4.399	6.525
South	UF1 - 70 cm					4.905							15.16
South	UF2 - 20 cm	2.082	2.394	1.409	0.8168	1.27	1.477	1.288	1.238	1.311	1.328	1.492	1.356
South	UF2 - 50 cm	3.762	4.525	3.25	3.175	3.154	3.146	3.183	3.176	3.162	3.094	3.437	3.532
South	F1 - 20 cm	1.598	1.826	1.241	1.432	1.341	1.642	1.52	1.465	1.434	1.495	1.59	1.87
South	F1 - 50 cm	3.664	4.55	3.277	2.798	2.993	3.016	2.975	3.006	3.069	3.501	2.92	3.285
South	F2 - 20 cm	1.573	2.093	1.618	1.285	1.267	1.429	1.258	1.345	1.417	1.78	1.657	2.106
South	F2 - 50 cm	2.53	1.758	2.27	1.549	1.56	1.612	1.66	1.601	1.712	1.804	1.678	2.121
South	F3 - 20 cm	1.828	2.17	1.814	1.629	1.623	1.676	1.847	1.845	1.957	2.181	2.331	2.33
South	F3 - 50 cm	2.766	2.562	3.9	2.178	2.134	2.347	2.337	2.441	2.282	2.711	2.567	2.597

Table 23: Strontium concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.0819	0.06	0.0594	0.0449	0.0448			0.0245	
North	U1 - 50 cm	0.0708		0.0701	0.0833	0.0667	0.0674	0.0687	0.0743	0.0804		0.0864	0.0839
North	UF1 - 50 cm		0.0852	0.0899	0.108	0.0606	0.0585	0.0638	0.0663	0.064	0.0634	0.0609	0.0616
North	UF1 - 70 cm				0.092	0.0592	0.06	0.0592	0.0603	0.0602	0.0586	0.056	0.0557
North	UF2 - 20 cm	0.0618	0.0613	0.0624	0.0651	0.053	0.0497	0.0507	0	0.0523	0.049	0.042	0.0462
North	UF2 - 50 cm	0.077	0.0786	0.0742	0.0835	0.0413	0.041	0.0409	0.0419	0.0409	0.0405	0.0395	0.0395
North	F1 - 20 cm	0.0372	0.0429	0.0408	0.0397	0.036	0.0328	0.0345	0.0339	0.0333	0.0307	0.0299	0.0319
North	F1 - 50 cm	0.0762	0.0619	0.0702	0.0647	0.04	0.0377	0.0421	0.0426	0.0434	0.043	0.0414	0.0414
North	F2 - 20 cm	0.0386	0.039	0.0418	0.0446	0.0351	0.0353	0.036	0.0366	0.0377	0.0369	0.0346	0.0354
North	F2 - 50 cm	0.0451	0.0493	0.0426	0.0441	0.0291	0.0289	0.0296	0.0306	0.0307	0.0305	0.0295	0.03
North	F3 - 20 cm	0.0387	0.0372	0.0355	0.0386	0.0309	0.0272	0.0311	0.0323	0.0319	0.0323	0.031	0.0319
North	F3 - 50 cm	0.0432	0.0477	0.0369	0.037	0.0309	0.0276	0.0254	0.0326	0.0331	0.0335	0.0305	0.0292
Middle	U1 - 20 cm		0.0809	0.0756	0.0603	0.0436	0.0419	0.0468	0.0486	0.0485		0.0509	0.0498
Middle	U1 - 50 cm	0.088	0.0976	0.092	0.1261	0.0668	0.0678	0.0745	0.0764	0.0768	0.0793	0.0793	0.0816
Middle	UF1 - 50 cm		0.1551	0.1533	0.1983	0.098	0.099	0.0931	0.0925	0.0919	0.0927	0.0859	0.0869
Middle	UF1 - 70 cm		0.1578	0.1476	0.1493	0.0939	0.0928	0.0914	0.0922	0.0927	0.0925	0.0863	0.0873
Middle	UF2 - 20 cm	0.1003	0.1044	0.0989	0.1098	0.0796	0.0727	0.0734	0.0702	0.0659	0.0624	0.0683	0.0734
Middle	UF2 - 50 cm	0.1398	0.1492	0.1348	0.1429	0.0862	0.0876	0.0866	0.0892	0.0915	0.0919	0.0858	0.0862
Middle	F1 - 20 cm	0.0957	0.1151	0.1033	0.1256	0.0705	0.0707	0.0718	0.0759	0.0745	0.0765	0.0676	0.0663
Middle	F1 - 50 cm	0.131	0.1406	0.114	0.117	0.0797	0.0793	0.0791	0.0731	0.0823	0.0828	0.0771	0.0776
Middle	F2 - 20 cm	0.0786	0.0826	0.0718	0.0817	0.0564	0.0558	0.0576	0.0597	0.0615	0.0625	0.0598	0.0616
Middle	F2 - 50 cm	0.1107	0.1108	0.0872	0.1049	0.068	0.0697			0.0728	0.0713	0.0664	0.0676
Middle	F3 - 20 cm	0.0622	0.0667	0.0642	0.0779	0.0528	0.0504	0.0491	0.051	0.0506	0.0527	0.052	0.0537
Middle	F3 - 50 cm	0.113	0.1168	0.0991	0.1144	0.0738	0.0731	0.0723	0.0802	0.0811	0.081	0.0767	0.0786
South	U1 - 20 cm				0.056	0.0761		0.0646					0.0578
South	U1 - 50 cm				0.1183					0.1562			
South	UF1 - 50 cm			0.1299			0.0986	0.1164	0.118	0.1451	0.1274	0.1149	0.1341
South	UF1 - 70 cm					0.1144							0.1829
South	UF2 - 20 cm	0.0475	0.051	0.048	0.0294	0.0512	0.0537	0.0426	0.0476	0.0471	0.048	0.0448	0.044
South	UF2 - 50 cm	0.085	0.0963	0.0847	0.0542	0.061	0.0661	0.0626	0.0673	0.0648	0.0644	0.061	0.0624
South	F1 - 20 cm	0.0465	0.051	0.051	0.0427	0.0469	0.0504	0.0472	0.0479	0.0502	0.0486	0.0484	0.0512
South	F1 - 50 cm	0.1088	0.1137	0.1043	0.0696	0.0744	0.0756	0.0724	0.0767	0.0763	0.0724	0.0692	0.0706
South	F2 - 20 cm	0.0495	0.0561	0.0723	0.0492	0.0575	0.0549	0.0479	0.0507	0.0531	0.0521	0.0488	0.0516
South	F2 - 50 cm	0.0578	0.0496	0.0589	0.0439	0.0503	0.0553	0.053	0.0528	0.0532	0.0501	0.0493	0.0528
South	F3 - 20 cm	0.057	0.0681	0.0731	0.0559	0.0596	0.0623	0.0648	0.0629	0.0655	0.0647	0.0646	0.0657
South	F3 - 50 cm	0.0656	0.0559	0.0489	0.0397	0.0457	0.0487	0.0366	0.0479	0.0494	0.0467	0.0449	0.0429

Table 24: Total nitrogen concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.61	0.62	0.59	0.17	0.73			1.47	
North	U1 - 50 cm	0.34		0.23	0.13	0.1	0.11	0.59	0.22	0.26		0.28	0.37
North	UF1 - 50 cm		0.23	0.02	0.03	0.05	0.05	0.06	0.12	0.07	0.07	0.05	0.07
North	UF1 - 70 cm				0.03	0.02	0.7	0.12	0.48	0.44	0.29	0.17	0.11
North	UF2 - 20 cm	0.92	0.88	1.13	0.99	0.96	0.92	0.18	0.91	0.88	0.81	1.1	0.98
North	UF2 - 50 cm	0.2	0.07	0.08	0.05	0.07	0.06	0.19	0.08	0.07	0.05	0.04	0.01
North	F1 - 20 cm	0.7	0.61	0.64	0.48	0.56	0.65	0.13	0.67	0.9	1.1	1.01	1.12
North	F1 - 50 cm	0.9	0.72	0.55	0.44	0.44	0.43	0.1	0.33	0.45	0.51	0.47	0.4
North	F2 - 20 cm	1.03	0.98	0.91	0.82	0.89	0.93	0.13	0.91	1.08	1.09	1.25	1.15
North	F2 - 50 cm	1.03	0.88	0.71	0.67	0.69	0.57	0.31	0.62	0.75	0.7	0.73	0.69
North	F3 - 20 cm	0.99	0.97	0.9	0.92	0.94	1.13	1.08	1.07	1.4	1.45	1.57	1.42
North	F3 - 50 cm	0.92	1.03	0.84	0.81	0.82	0.92	0.65	0.83	1.03	0.97	0.99	0.8
Middle	U1 - 20 cm		0.37	0.28	0.35	0.3	0.29	0.38	0.34	0.5		0.59	0.54
Middle	U1 - 50 cm	0.21	0.21	0.14	0.25	0.3	0.41	0.33	0.27	0.27	0.31	0.17	0.21
Middle	UF1 - 50 cm		0.25	0.12	0.11	0.1	0.05	0.08	0.06	0.09	0.12	0.11	0.03
Middle	UF1 - 70 cm		0.27	0.18	0.02	0.1	0.06	0.03	0.08	0.06	0.06	0.02	0.04
Middle	UF2 - 20 cm	0.78	0.65	0.57	0.72	0.55	0.66	0.69	0.83	0.98	0.96	0.88	0.81
Middle	UF2 - 50 cm	0.43	0.33	0.28	0.3	0.28	0.23	0.25	0.26	0.34	0.32	0.29	0.23
Middle	F1 - 20 cm	0.94	0.88	0.88	0.83	0.64	0.71	0.72	0.97	0.99	0.98	0.89	0.89
Middle	F1 - 50 cm	0.32	0.31	0.25	0.25	0.26	0.23	0.27	0.28	0.31	0.38	0.24	0.25
Middle	F2 - 20 cm	0.61	0.47	0.48	0.47	0.44	0.5	0.5	0.72	0.79	0.82	0.81	0.77
Middle	F2 - 50 cm	1.1	0.88	0.96	0.99	0.79	0.8			1.19	1.14	0.91	0.91
Middle	F3 - 20 cm	0.32	0.35	0.36	0.4	0.48	0.46	0.53	0.57	0.62	0.89	0.73	0.66
Middle	F3 - 50 cm	1.82	1.45	1.51	1.55	1.59	1.51	1.52	1.86	1.86	1.9	1.65	1.6
South	U1 - 20 cm				0.47	0.75		0.54					1.11
South	U1 - 50 cm				0.05					1.05			
South	UF1 - 50 cm			0.03			0.06	0.05	0.01	0.09	0.1	0	0.03
South	UF1 - 70 cm				0.35	0.03							0.83
South	UF2 - 20 cm	0.48	0.48	0.47	0.49	0.68	0.75	0.66	0.81	0.88	0.92	1.04	0.8
South	UF2 - 50 cm	1.39	1.27	1.26	1.49	1.3	1.15	1.03	1.55	1.51	1.5	1.32	1.16
South	F1 - 20 cm	0.65	0.75	0.81	1	1.06	0.95	0.88	1.31	1.47	1.7	1.43	1.41
South	F1 - 50 cm	2.22	2.11	2.26	2.34	2.47	2.32	2.15	2.67	2.82	2.69	2.61	2.18
South	F2 - 20 cm	0.36	0.44	0.39	0.57	0.73	0.85	0.97	1.04	1.11	1.31	1.12	1.15
South	F2 - 50 cm	0.8	0.95	0.77	0.93	0.99	1.11	0.93	1.26	1.24	1.52	1.48	1.33
South	F3 - 20 cm	0.47	0.5	0.44	0.51	0.59	0.74	0.65	0.63	0.76	0.84	0.63	0.46
South	F3 - 50 cm	1.15	1.06	0.92	1.16	1.21	0.05	1.22	1.31	1.45	1.53	1.3	1.04

Table 25: Total phosphorus concentrations (mg L^{-1}) at each piezometer location for all data collection days.

		Date											
Transect	Piezometer	18-Jun	22-Jun	2-Jul	12-Jul	29-Jul	3-Aug	9-Aug	17-Aug	22-Aug	27-Aug	6-Sep	12-Sep
North	U1 - 20 cm				0.07	0	0	0.01	0.02			0.1	
North	U1 - 50 cm	0.08		0.06	0.04	0	0	0.01	0	0		0	0
North	UF1 - 50 cm		0.05	0	0.02	0	0	0	0	0.01	0.02	0	0
North	UF1 - 70 cm				0.01	0	0.07	0.01	0	0.03	0.03	0.01	0
North	UF2 - 20 cm	0.05	0.05	0.06	0.06	0	0	0	0	0.01	0.02	0	0
North	UF2 - 50 cm	0.03	0.05	0.05	0.03	0	0	0	0	0.02	0.02	0.01	0
North	F1 - 20 cm	0.06	0	0	0.01	0.01	0	0	0	0.02	0.06	0	0.01
North	F1 - 50 cm	0.08	0.06	0.05	0.05	0	0	0.2	0	0.03	0.02	0.02	0
North	F2 - 20 cm	0.05	0.05	0.05	0.06	0.01	0.01	0	0.02	0.08	0.09	0.08	0.08
North	F2 - 50 cm	0.06	0.07	0.06	0.07	0.01	0.03	0	0.01	0.02	0.04	0.06	0.07
North	F3 - 20 cm	0.05	0.05	0.05	0.08	0.07	0	0.1	0.11	0.1	0.1	0.09	0.09
North	F3 - 50 cm	0.05	0.06	0.05	0.06	0	0.03	0.02	0.03	0.02	0.04	0	0.01
Middle	U1 - 20 cm		0.07	0.02	0.06	0	0	0.02	0	0.01		0	0
Middle	U1 - 50 cm	0.05	0.05	0.05	0.04	0	0	0	0	0.01	0.01	0	0
Middle	UF1 - 50 cm		0.05	0.01	0.07	0	0	0.01	0.01	0.01	0.01	0	0
Middle	UF1 - 70 cm		0.06	0.06	0.06	0	0	0.02	0	0.04	0.04	0.06	0.01
Middle	UF2 - 20 cm	0.08	0.06	0.06	0.09	0	0.08	0	0.11	0.12	0.12	0.07	0.09
Middle	UF2 - 50 cm	0.07	0.06	0.06	0.06	0.01	0	0.02	0.02	0.08	0.08	0.05	0.08
Middle	F1 - 20 cm	0.08	0.05	0.09	0.12	0.07	0.07	0.01	0.09	0.1	0.09	0.07	0.09
Middle	F1 - 50 cm	0.07	0.07	0.04	0.06	0	0	0.02	0.03	0.08	0.05	0.02	0
Middle	F2 - 20 cm	0.05	0.02	0.06	0.07	0	0	0.02	0.08	0.09	0.08	0.08	0.09
Middle	F2 - 50 cm	0.1	0.07	0.07	0.11	0.02	0			0.09	0.06	0.02	0.06
Middle	F3 - 20 cm	0.01	0.05	0.06	0.06	0.03	0	0.1	0.08	0.08	0.08	0.07	0.07
Middle	F3 - 50 cm	0.15	0.11	0.08	0.15	0.09	0.08	0.1	0.14	0.15	0.13	0.07	0.11
South	U1 - 20 cm				0.08	0		0					0.01
South	U1 - 50 cm				0					0.03			
South	UF1 - 50 cm			0.03			0.03	0	0.03	0.03	0.03	0.07	0.08
South	UF1 - 70 cm				0.4	0							0.06
South	UF2 - 20 cm	0.05	0.06	0.07	0.06	0.1	0.11	0.02	0.11	0.1	0.08	0.08	0.09
South	UF2 - 50 cm	0.23	0.24	0.28	0.06	0.32	0.26	0.2	0.33	0.27	0.24	0.16	0.12
South	F1 - 20 cm	0.05	0.07	0.07	0.14	0.14	0.05	0.04	0.16	0.18	0.17	0.1	0.16
South	F1 - 50 cm	0.12	0.11	0.11	0.15	0.19	0.2	0.01	0.09	0.16	0.03	0.03	0
South	F2 - 20 cm	0.05	0.12	0.14	0.16	0.15	0.17	0.19	0.15	0.21	0.21	0.15	0.16
South	F2 - 50 cm	0.1	0.1	0.09	0.16	0.11	0.13	0.12	0.13	0.12	0.13	0.15	0.17
South	F3 - 20 cm	0.05	0.06	0.07	0.12	0.13	0.11	0.12	0.1	0.14	0.15	0.08	0.09
South	F3 - 50 cm	0.06	0.07	0.07	0.1	0.08	0.11	0.1	0.08	0.12	0.09	0.08	0.06